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Coherent elastic neutrino-nucleus scattering in the Standard Model and beyond

International Conference on Neutrinos and Dark Matter (NuDM-2022)

25-28 September 2022
Sharm El-Sheikh, Egypt- Online

Outline

Introduction and motivations

- Coherent elastic neutrino nucleus scattering (CEνNS)
- Observation of CEνNS at COHERENT
- Evidence of CEνNS at Dresden-II

Physics potential of CEνNS

- SM physics (weak mixing angle)
- New interactions (light vector mediator)
- New interactions (light scalar mediator)
- Sterile neutrino dipole moment

Impact on the neutrino floor

- Data-driven analysis
- Weak mixing angle
- New interactions (light vector mediator)
- New interactions (light scalar mediator)

Summary

Coherent Elastic Neutrino-Nucleus Scattering

- NC (flavour-independent) process: $\nu + N(A,Z) \rightarrow \nu + N(A,Z)$

- CEνNS occurs when the neutrino energy E_ν is such that nucleon amplitudes sum up coherently ($|\vec{q}| \leq 1/R_{nucleus}$):
  => cross section enhancement $\sigma \sim$ (#scatter targets)^2
  => upper limit on neutrino energy (up to $E_\nu \sim 100$ MeV)

- Total cross section scales approximately like N^2

$$\frac{d\sigma}{dE_R} \propto N^2$$

- Can be few orders of magnitude larger than inverse beta decay process used to first observe neutrinos

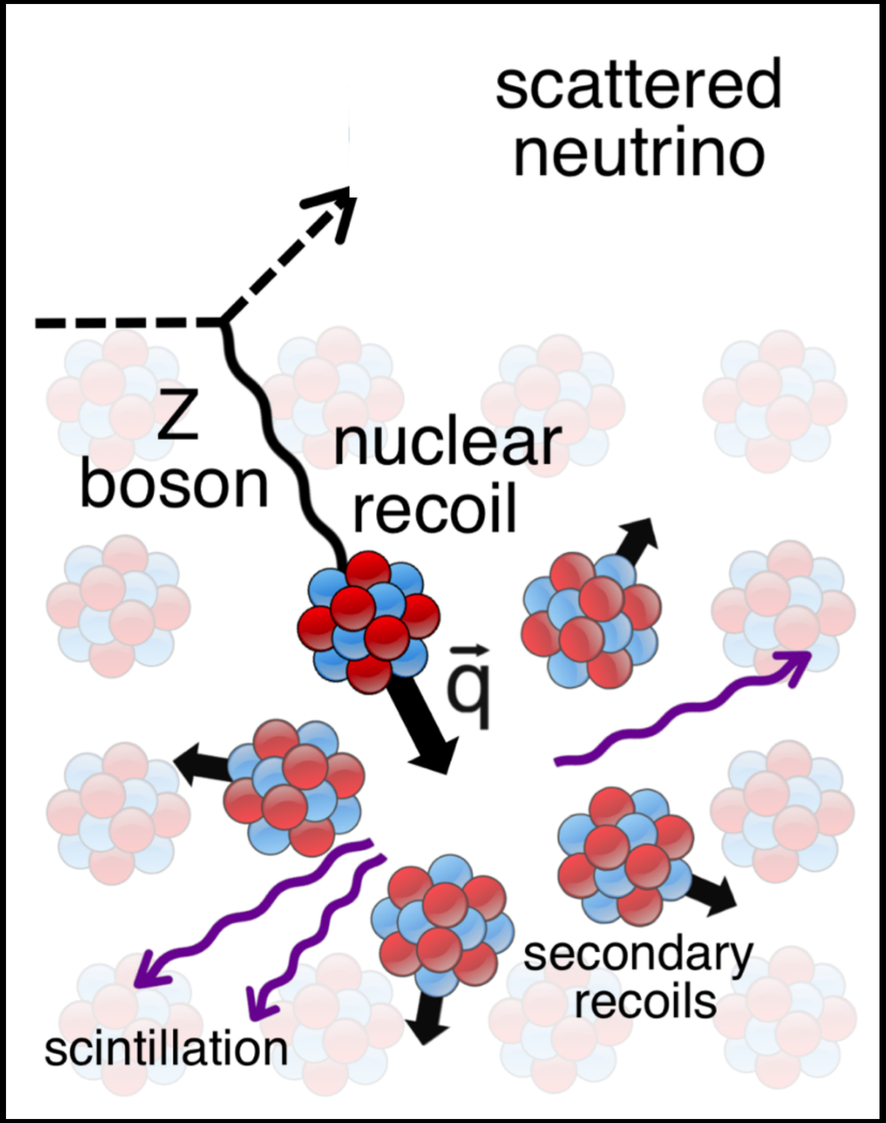
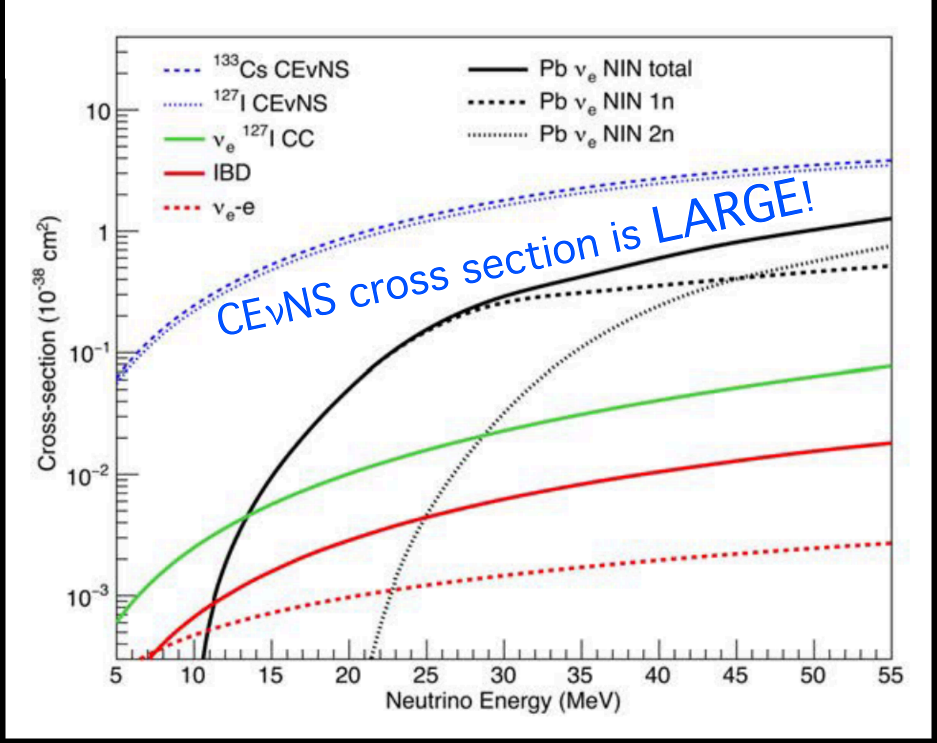


Image adapted from COHERENT exp.

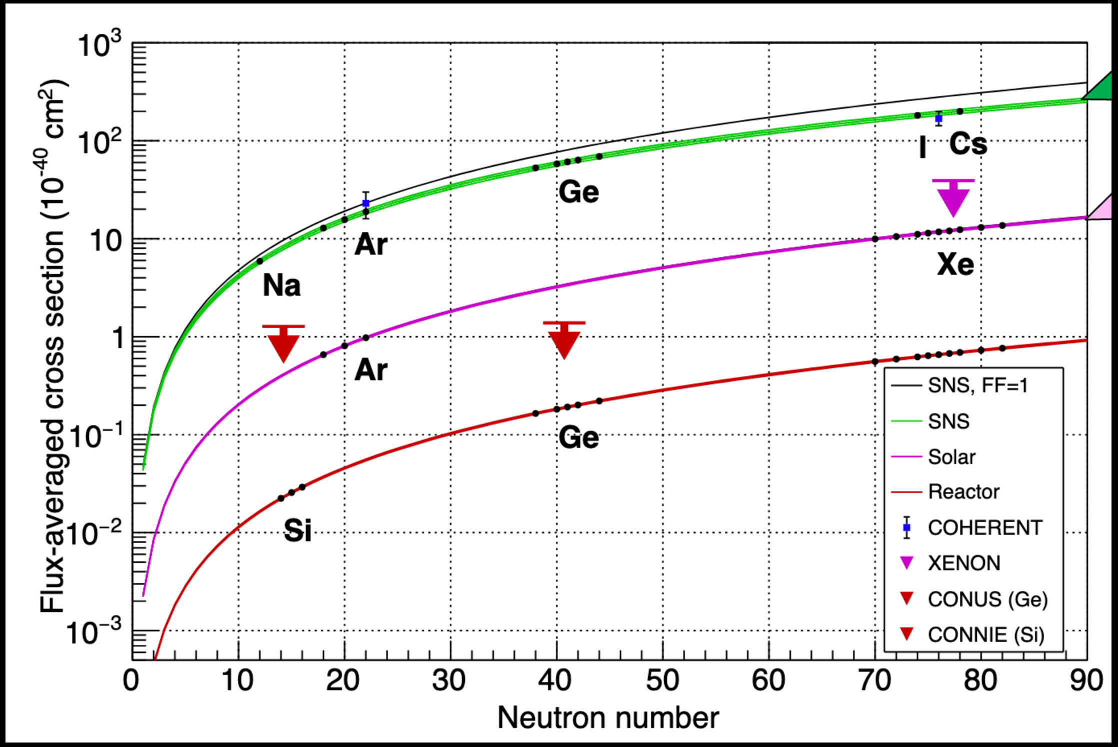
D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

Coherent Elastic Neutrino-Nucleus Scattering

- First theoretically predicted in 1974 — D.Z. Freedman, Phys. Rev. D 9 (1974); V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)
- CEνNS is an exceptionally challenging process to observe
- Despite its large cross section, not observed for years due to tiny nuclear recoil energies
  - Heavier nuclei: higher cross section but lower recoil
  - Both cross-section and maximum recoil energy increase with neutrino energy
  - Max recoil energy: $E_R^{\max} = \frac{2E_\nu^2}{m_N}$

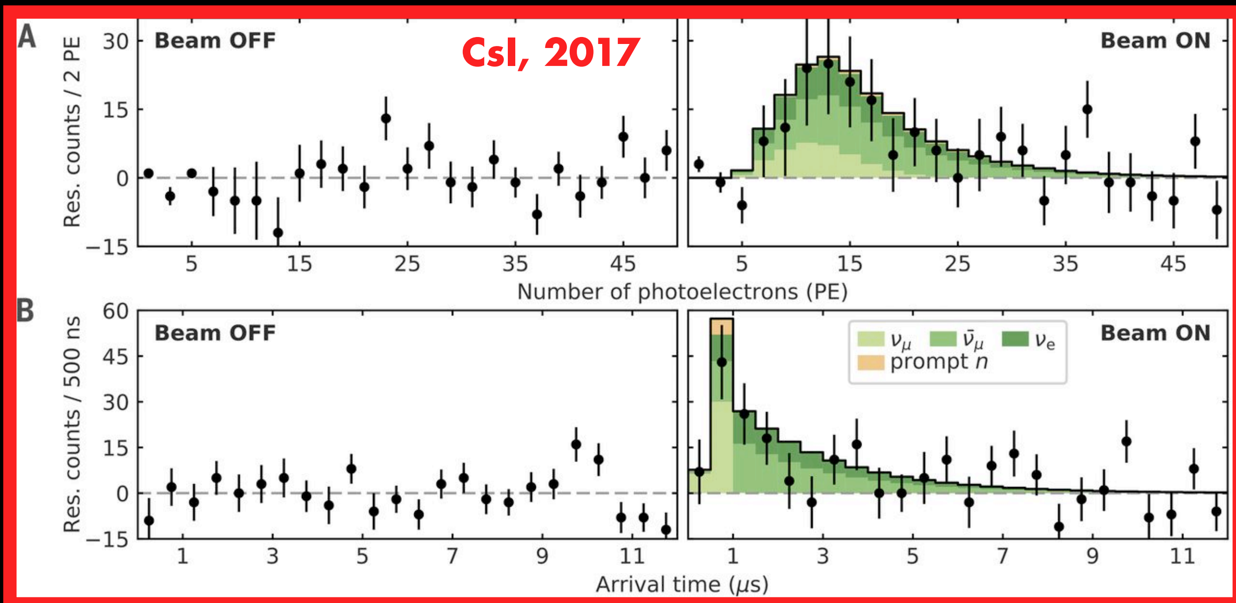


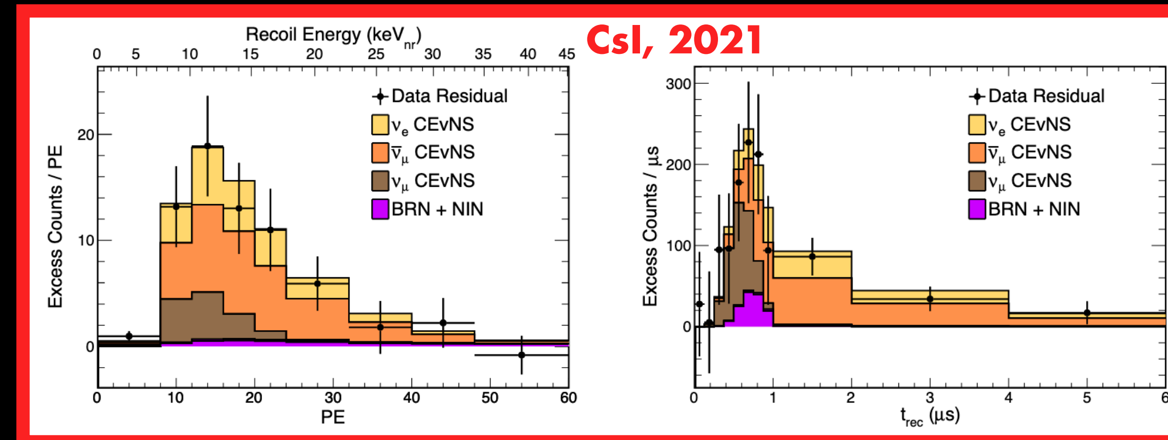
D. Akimov et al. (COHERENT). Science 357, 1123–1126 (2017)

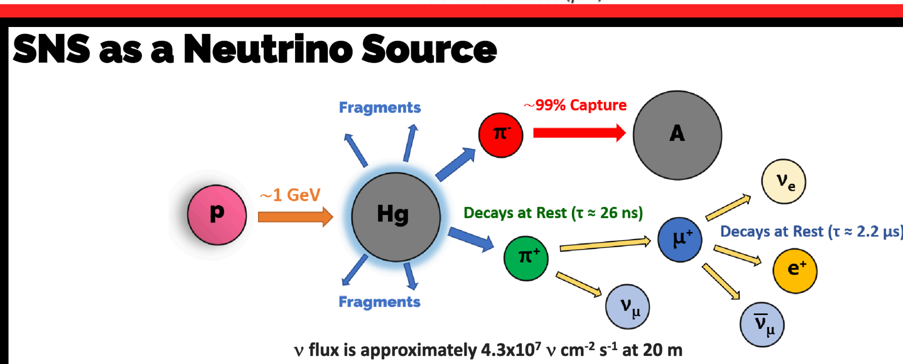


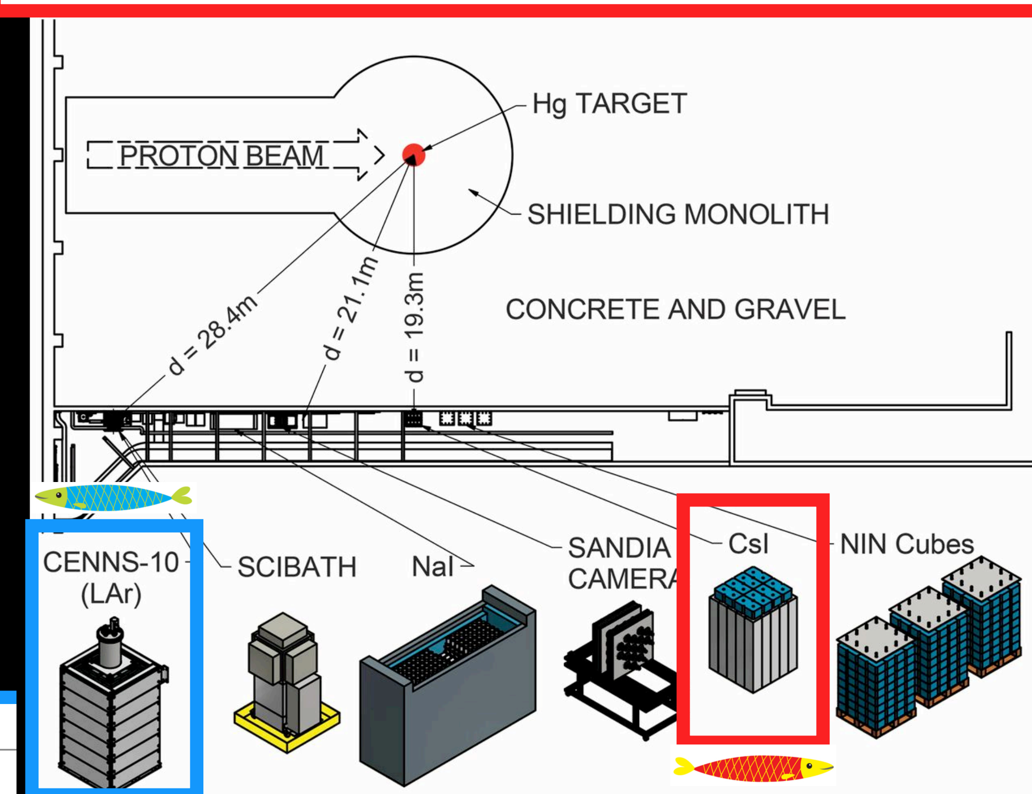
Credit to K. Scholberg @ISAPP 2021

Observation of CEνNS by COHERENT



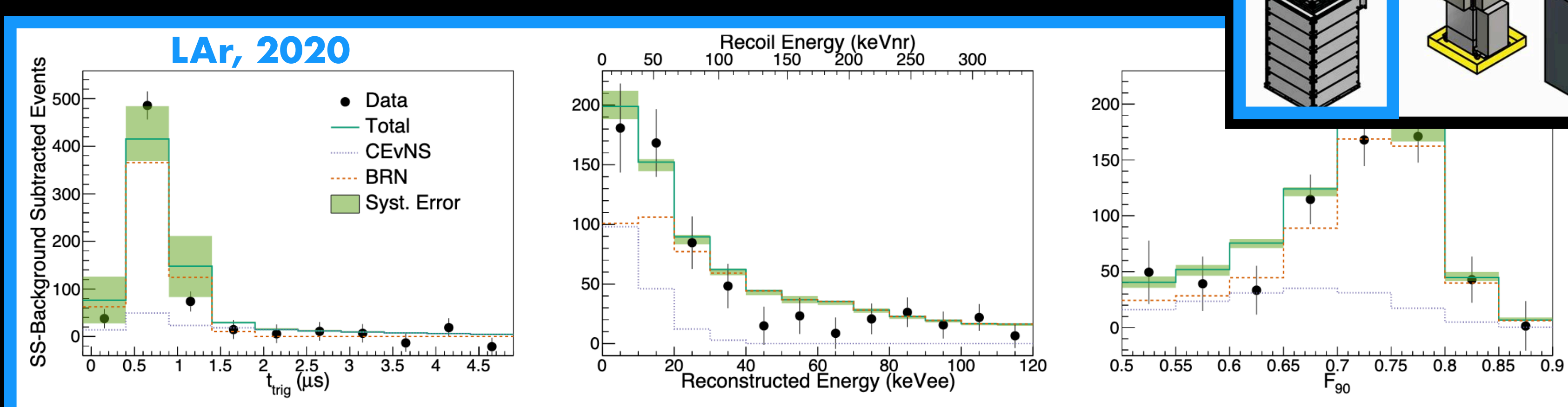






π-decay at rest, several neutrino flavours

neutrino flux at 20m: 4.3x10^7 neutrinos/sec/cm^2



D. Akimov et al. (COHERENT). Science 357, 1123–1126 (2017)

D. Akimov et al. (COHERENT). 2110.07730

D. Akimov et al. (COHERENT). Phys. Rev. Lett. 126, 012002 (2021)

Daughhetee, BNL Physics Seminar 2020

Evidence of CEνNS ? at CC-1701 (Dresden-II reactor)

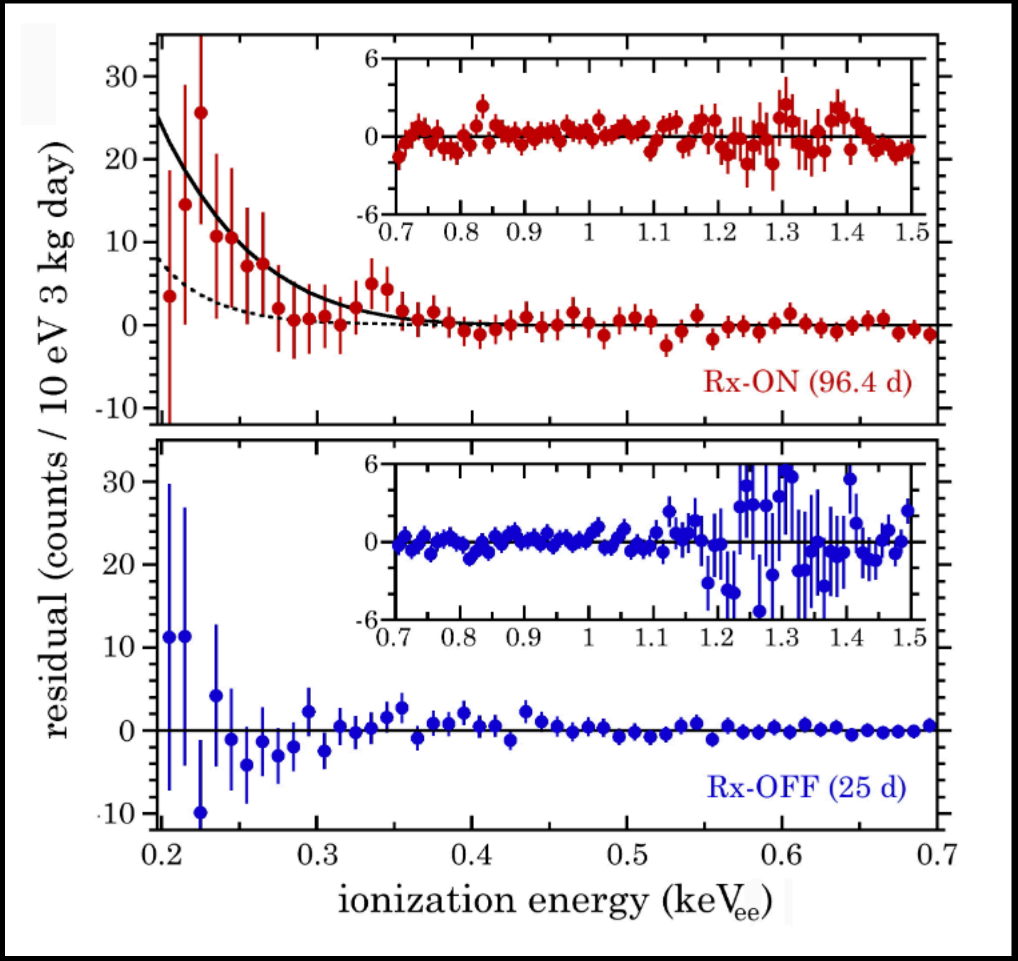
Neutrino source: Dresden-II boiling water reactor (USA) 2.96GW → 4.8 x10^{13} neutrinos/sec/cm^2

Detector: NCC-1701, a 2.924 kg ultra-low noise p-type point contact (PPC) Germanium detector

- low energy threshold (0.2 keV_{ee})
- distance to core: 10.39m
- 96.4-day exposure

CEνNS results: suggestive evidence of CEνNS is reported with strong preference (with respect to the background-only hypothesis)

- strongly dependent on quenching factor model



Colaresi, Collar, Hossbach, Lewis, Yocum, arXiv:2202.09672

Coherent Elastic Neutrino-Nucleus Scattering

CEνNS has a well-calculable cross-section in the SM:

(probability of kicking a nucleus with nuclear recoil energy T)

Fermi constant (SM parameter) — Kinematics — Nuclear Form Factor: F=1 full coherence

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right) Q_W^2 \left[F_W(q^2)\right]^2 + \frac{G_F^2 M}{4\pi}\left(1 + \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right) F_A(q^2)$$

Weak nuclear charge

$$Q_W = \left[Z(1 - 4\sin^2\theta_W) - N\right]$$

$s_W^2 = 0.23 \rightarrow$ protons unimportant

Neutron contribution dominates

- E_ν: is the incident neutrino energy
- M : the nuclear mass of the detector material
- 3-momentum transfer $q^2 = 2MT$

Axial contribution is small for most nuclei, spin-dependent.
It vanishes for nuclei with even number of protons and neutrons

Freedman, PRD 9 (1974) 1389; Drukier, Stodolsky, PRD 30 (1984) 2295; Barranco, Miranda, Rashba, hep-ph/0508299

Physics potential of CEνNS

EW precision tests:
- Weak mixing angle

Nuclear physics
- Nuclear form factors
- Neutron radius and “skin”

Supernovae

Solar neutrinos

Brdar and Rodejohann, arXiv:1810.03626; Chang and Liao, arXiv:2002.10275; Li et al, arXiv:2005.01543; CONUS, arXiv:2110.02174; Cadeddu et al, arXiv:1710.02730, arXiv:2005.01645, arXiv:1908.06045; Aristizabal Sierra et al, arXiv:1902.07398; Huang and Chen, arXiv:1902.07625; Papoulias et al, arXiv:1903.03722, arXiv:1907.11644; Miranda et al, arXiv:2003.12050 Papoulias et al, arXiv:1711.09773, arXiv:1907.11644; Cadeddu et al, arXiv:1808.10202, arXiv:2005.01645, arXiv:1908.06045, arXiv:2205.09484; Huang and Chen, arXiv:1902.07625; Miranda et al, arXiv:1902.09036, arXiv:2003.12050; Khan and Rodejohann, arXiv:1907.12444; COHERENT, arXiv:2110.07730; Papoulias and Kosmas, arXiv:1711.09773; Blanco et al, arXiv:1901.08094; Miranda et al, arXiv:1902.09036

New neutrino interactions
- Non-standard interactions
- Generalised interactions
- New mediators

Neutrino properties
- Neutrino charge radius
- Magnetic moments

Sterile neutrinos

Dark matter

Cerdeño et al, arXiv:1604.01025; Farzan et al, arXiv:1802.05171; Aristizabal Sierra et al, arXiv:1806.07424; Khan and Rodejohann, arXiv:1907.12444; Aristizabal Sierra et al, arXiv:1910.12437; Miranda et al, arXiv:2003.12050; Aristizabal Sierra et al, JHEP 09 (2019) 069; Suliga and Tamborra, arXiv:2010.14545; CONUS, arXiv:2110.02174; Li and Xia, arXiv:2201.05015; Atzori Corona et al, arXiv:2202.11002; Liao et al, arXiv:2202.10622; Coloma et al, arXiv:2202.10829; Lindner et al, arXiv:1612.04150; Aristizabal Sierra et al, arXiv:1806.07424; Aristizabal Sierra et al, JCAP 01 (2022) 01, 055, …………

Physics potential of CEνNS

- SM precision tests:
  - Weak mixing angle
- Nuclear physics
  - Nuclear form factors
  - Neutron radius and "skin"
- Supernovae
- Solar neutrinos
- New neutrino interactions
  - Non-standard interactions
  - Generalised interactions
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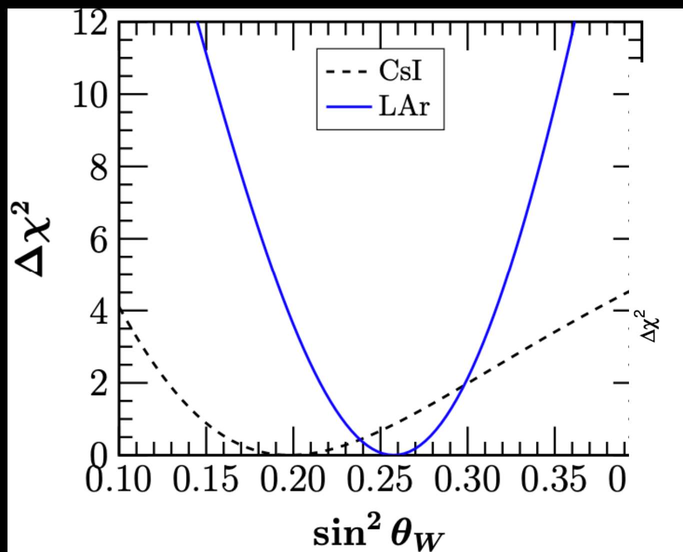
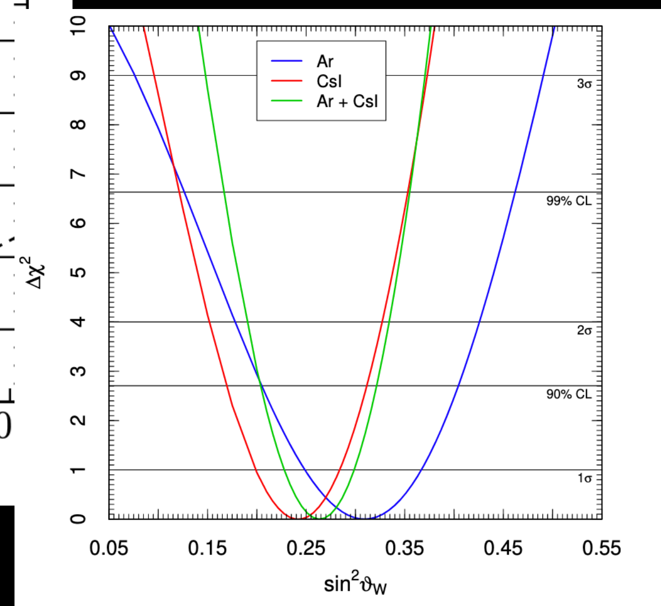
  - Neutrino charge radius
  - Magnetic moments
- Sterile neutrinos
- Dark matter

SM precision tests: weak mixing angle

COHERENT CsI + LAr

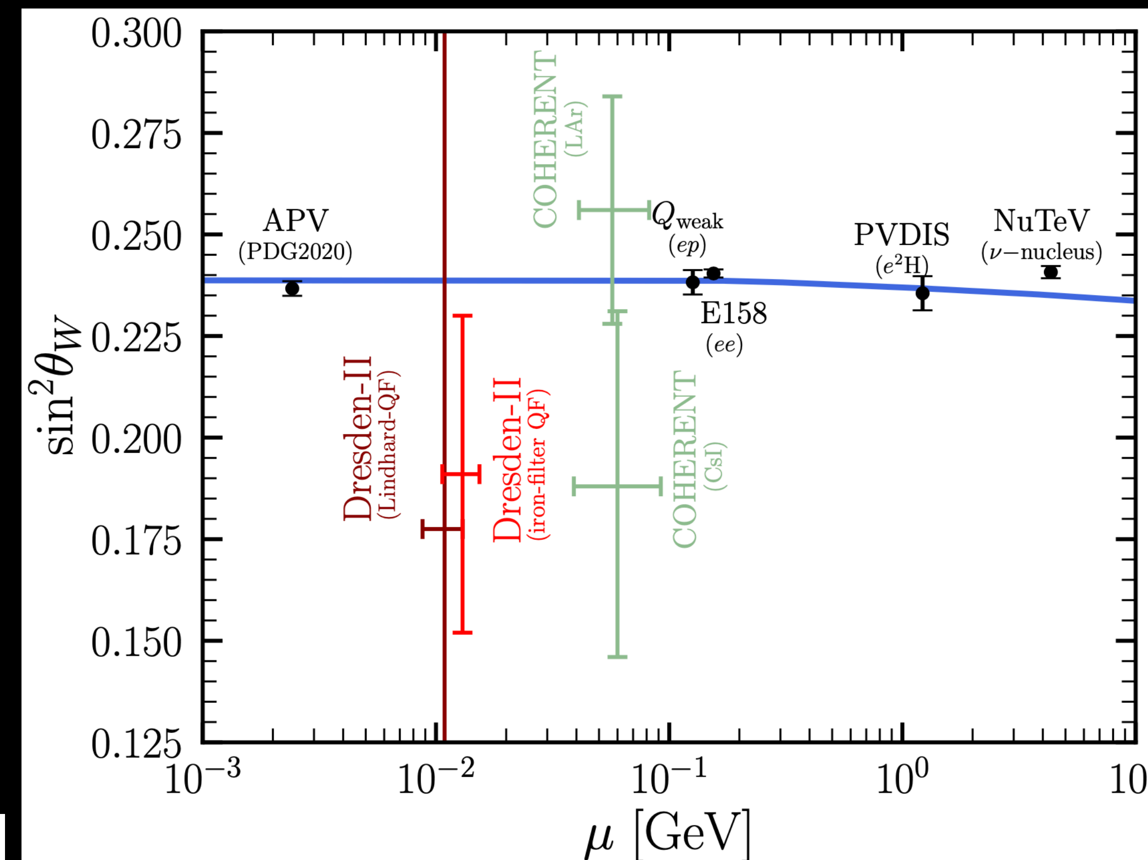


Miranda et al. JHEP 05 (2020) 130

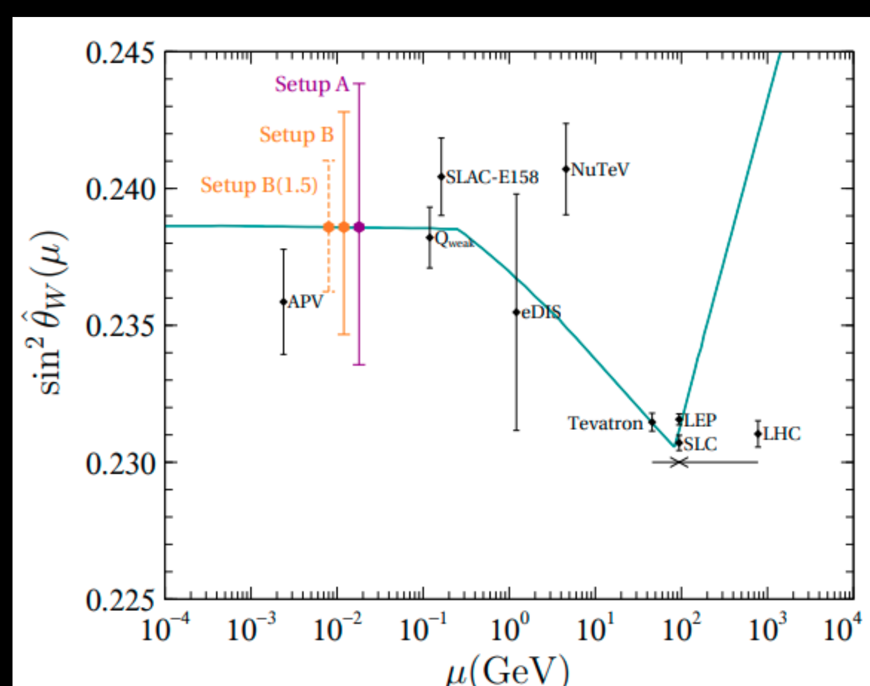


Cadeddu et al. 2005.01645

Dresden-II Ge



Aristizabal, VDR, Papoulias JHEP 09 (2022) 076



SBC LAr

[SBC Collaboration] L. J. Flores et al. Phys.Rev.D 103 (2021) 9, L091301

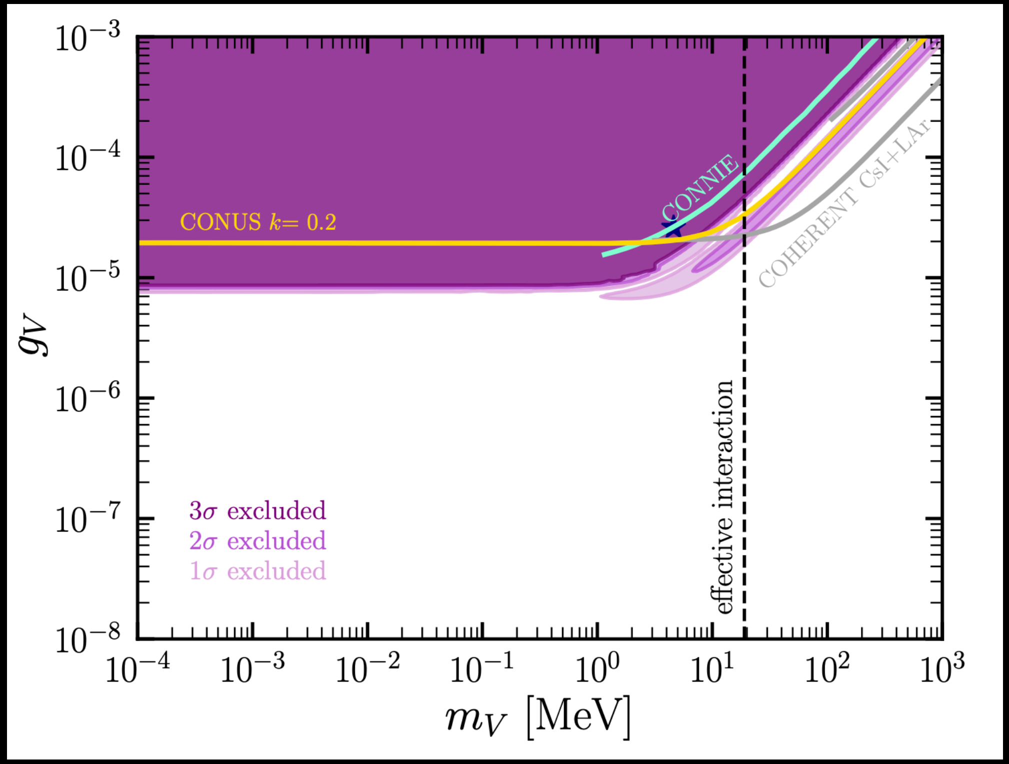
New neutrino interactions

Light vector mediator

$$\left.\frac{d\sigma}{dE_r}\right|_{\mathrm{NGI}} = \frac{G_F^2}{2\pi} m_N F^2(q^2)\left[\xi_S^2 \frac{2E_r}{E_r^{\max}} + \xi_V^2\left(2 - \frac{2E_r}{E_r^{\max}}\right) + \xi_T^2\left(2 - \frac{E_r}{E_r^{\max}}\right)\right]$$

$$C_X = \frac{1}{\sqrt{2}G_F}\frac{3A\, g_V^2}{2m_N E_r + m_X^2}$$

Dresden-II (Ge) - mod. Lindhard



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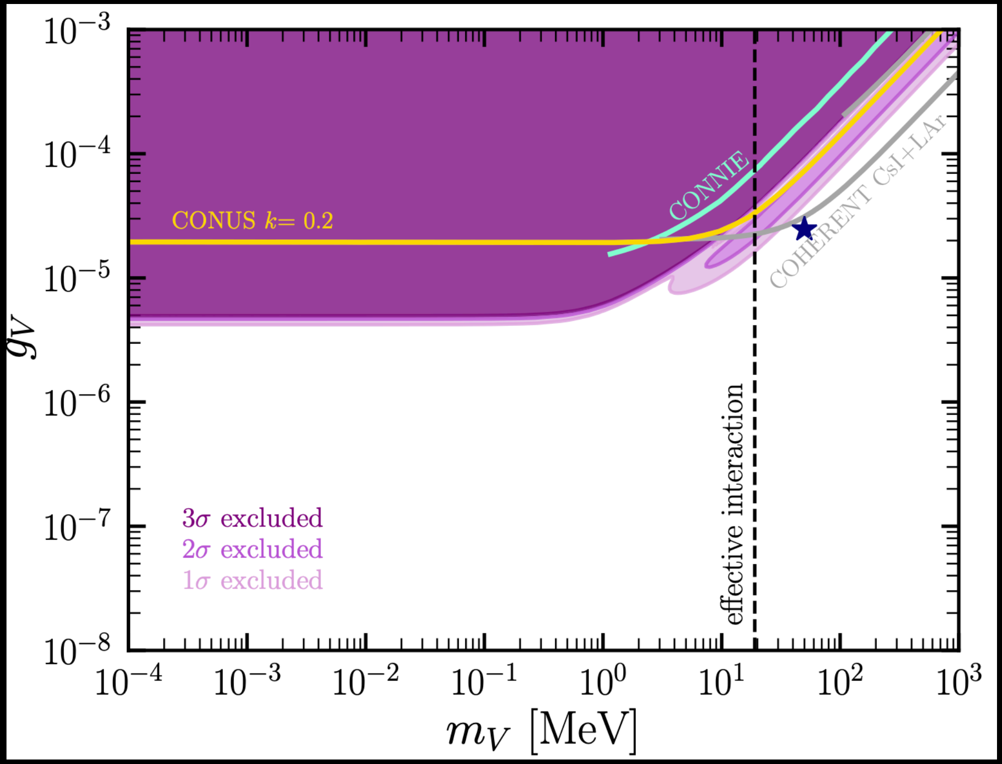
Dresden-II (Ge) - iron filter



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Possible degeneracy and cancellation with the SM contribution

Complementary analyses in: J. Liao, H. Liu, and D. Marfatia, 2202.10622
Coloma et al. 2202.10829, Atzori-Corona et al. 2205.09484, A. Khan 2203.08892

New neutrino interactions

Light scalar mediator

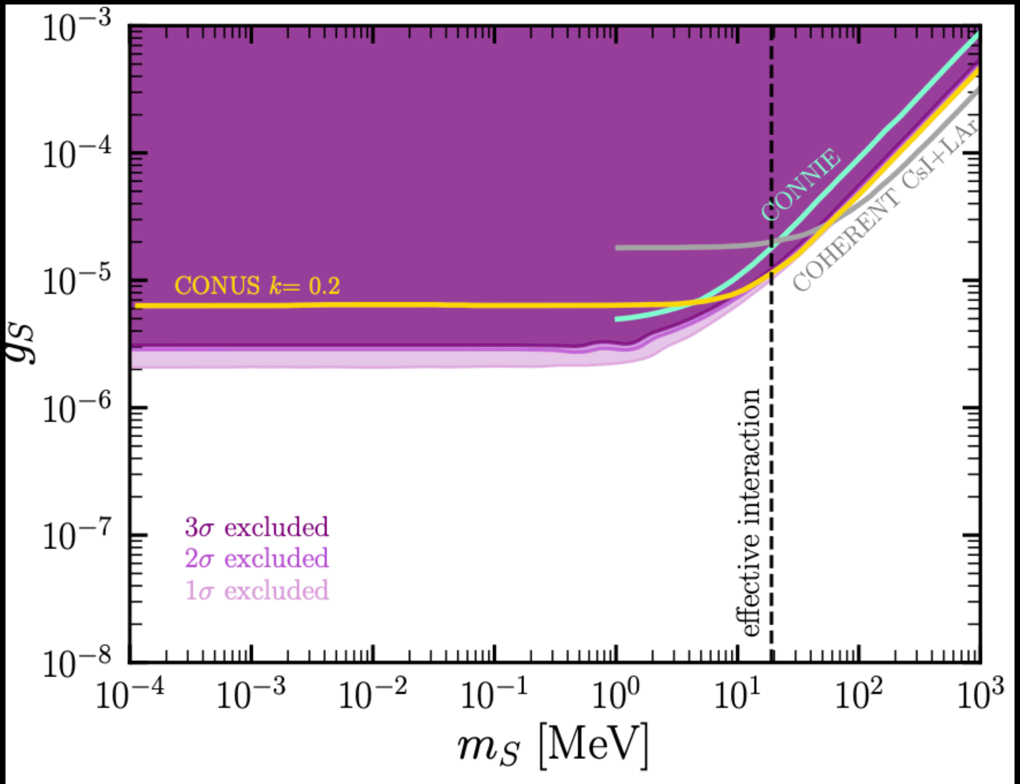
$$\left.\frac{d\sigma}{dE_r}\right|_{\text{NGI}} = \frac{G_F^2}{2\pi} m_N F^2(q^2) \left[\xi_S^2 \frac{2E_r}{E_r^{\max}} + \xi_V^2 \left(2 - \frac{2E_r}{E_r^{\max}}\right) + \xi_T^2 \left(2 - \frac{E_r}{E_r^{\max}}\right) \right]$$

$$\xi_S^2 = C_S^2$$

$$C_X = \frac{1}{\sqrt{2} G_F} \frac{f_X \overline{C}_X}{2 m_N E_r + m_X^2}$$

$$\overline{C}_S = Z \sum_q \frac{m_p}{m_q} f_{T_q}^p g_S^q + (A - Z) \sum_q \frac{m_n}{m_q} f_{T_q}^n g_S^q$$

Dresden-II (Ge) - mod. Lindhard



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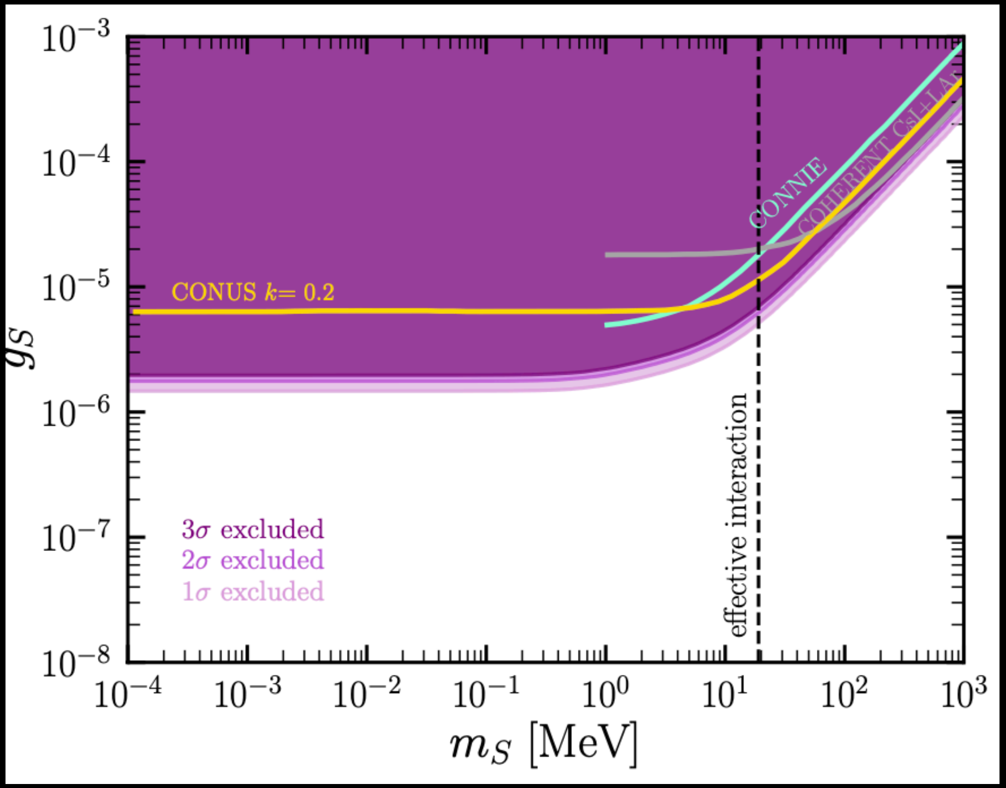

Aristizabal, VDR, Papoulias JHEP 09 (2022) 076

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Coloma et al. 2202.10829, Atzori-Corona et al. 2205.09484, A. Khan 2203.08892

Sterile neutrino dipole portal

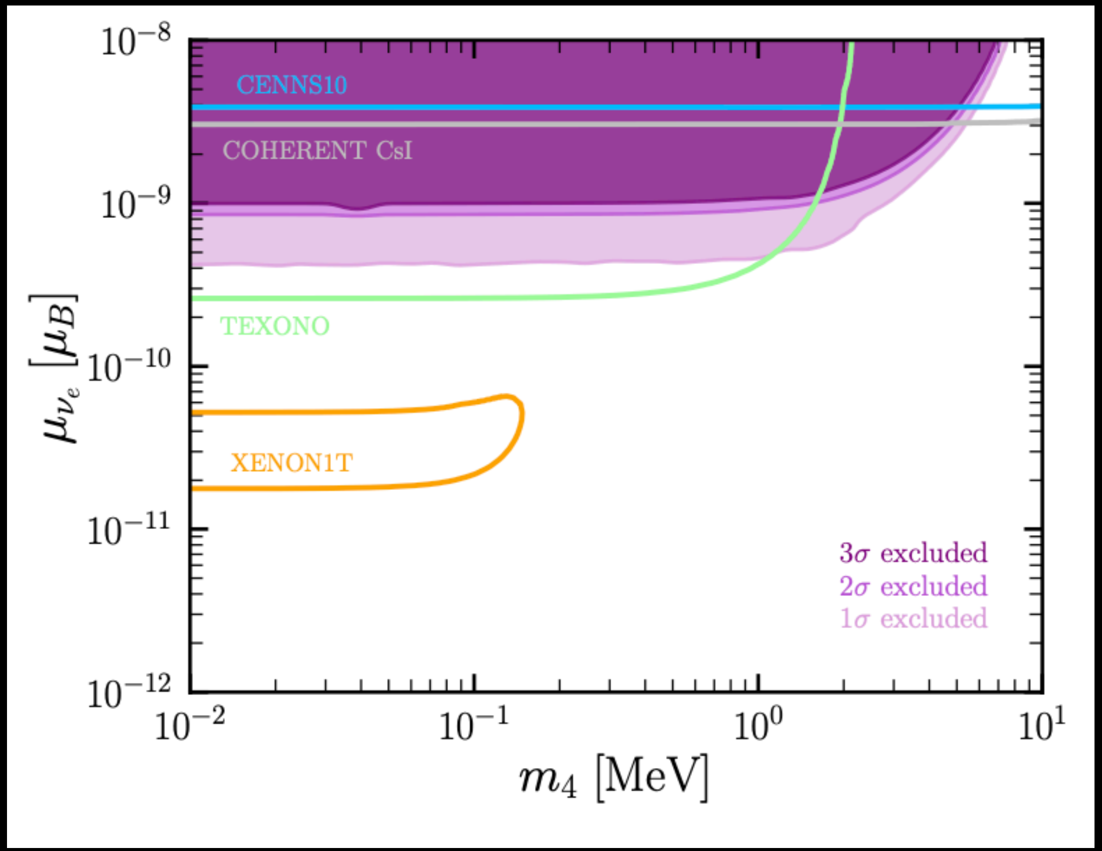
Transition of an active neutrino to a massive sterile state, induced by a magnetic coupling:
$\nu_L + N \rightarrow F_4 + N$

$$\mathcal{L} = \bar{\nu}\,\sigma_{\mu\nu}\,\lambda\,\nu_R\,F^{\mu\nu} + \text{H.c.}$$

$$m_4^2 \lesssim 2 m_N E_r \left(\sqrt{\frac{2}{m_N E_r}} E_\nu - 1 \right)$$

$$\left.\frac{d\sigma}{dE_r}\right|_{\text{DP}} = \alpha_{\text{EM}}\,\mu^2_{\nu,\text{Eff}}\,F^2(q^2)Z^2 \left[\frac{1}{E_r} - \frac{1}{E_\nu} - \frac{m_4^2}{2E_\nu E_r m_N}\left(1 - \frac{E_r}{2E_\nu} + \frac{m_N}{2E_\nu}\right) + \frac{m_4^4 (E_r - m_N)}{8E_\nu^2 E_r^2 m_N^2} \right]$$

Dresden-II (Ge) - mod. Lindhard



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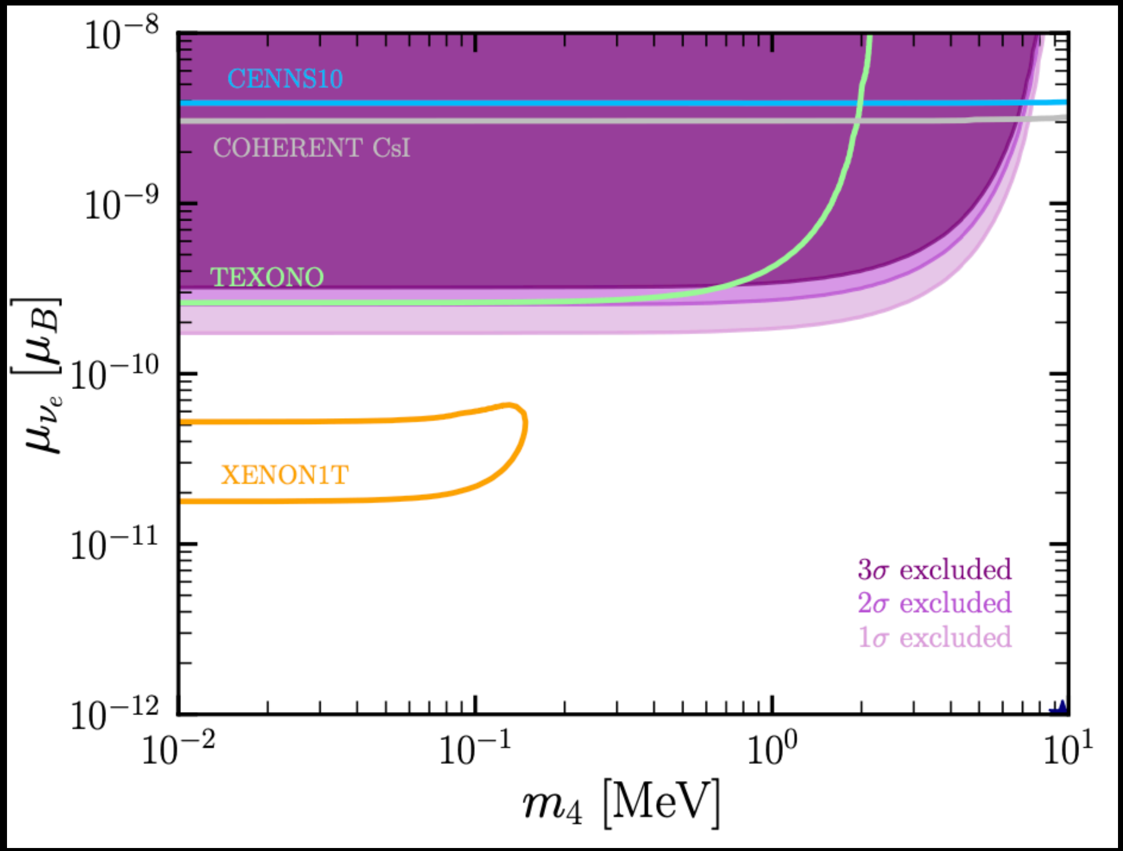
Dresden-II (Ge) - iron filter



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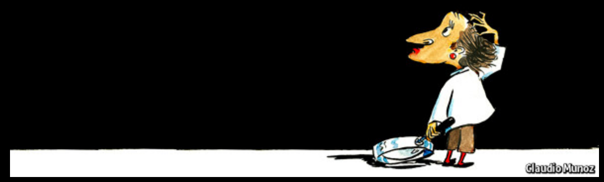
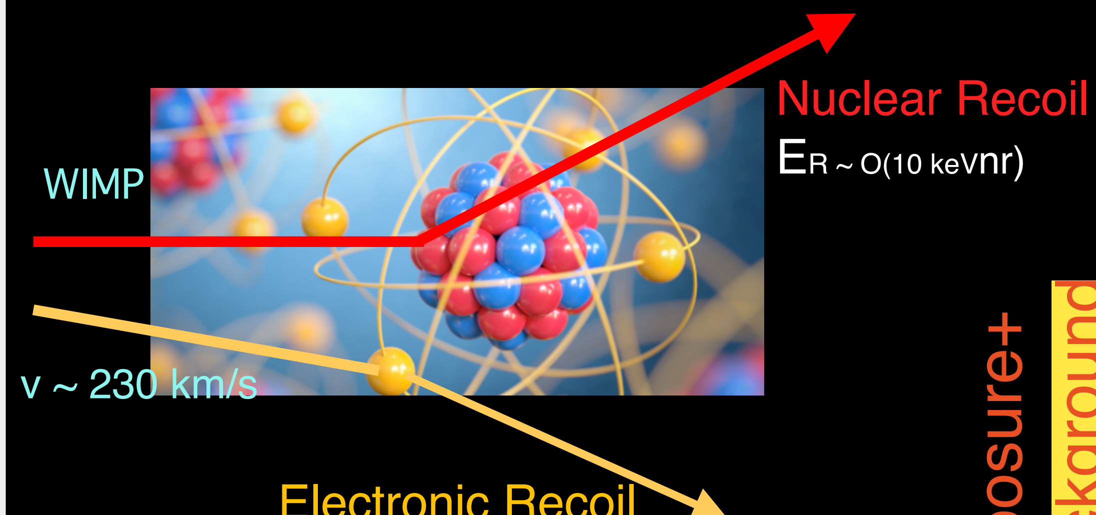
Direct WIMP Searches

If DM is made of particles that interact among themselves and with SM particles (e.g. WIMPs) we may hope to detect it. One strategy:

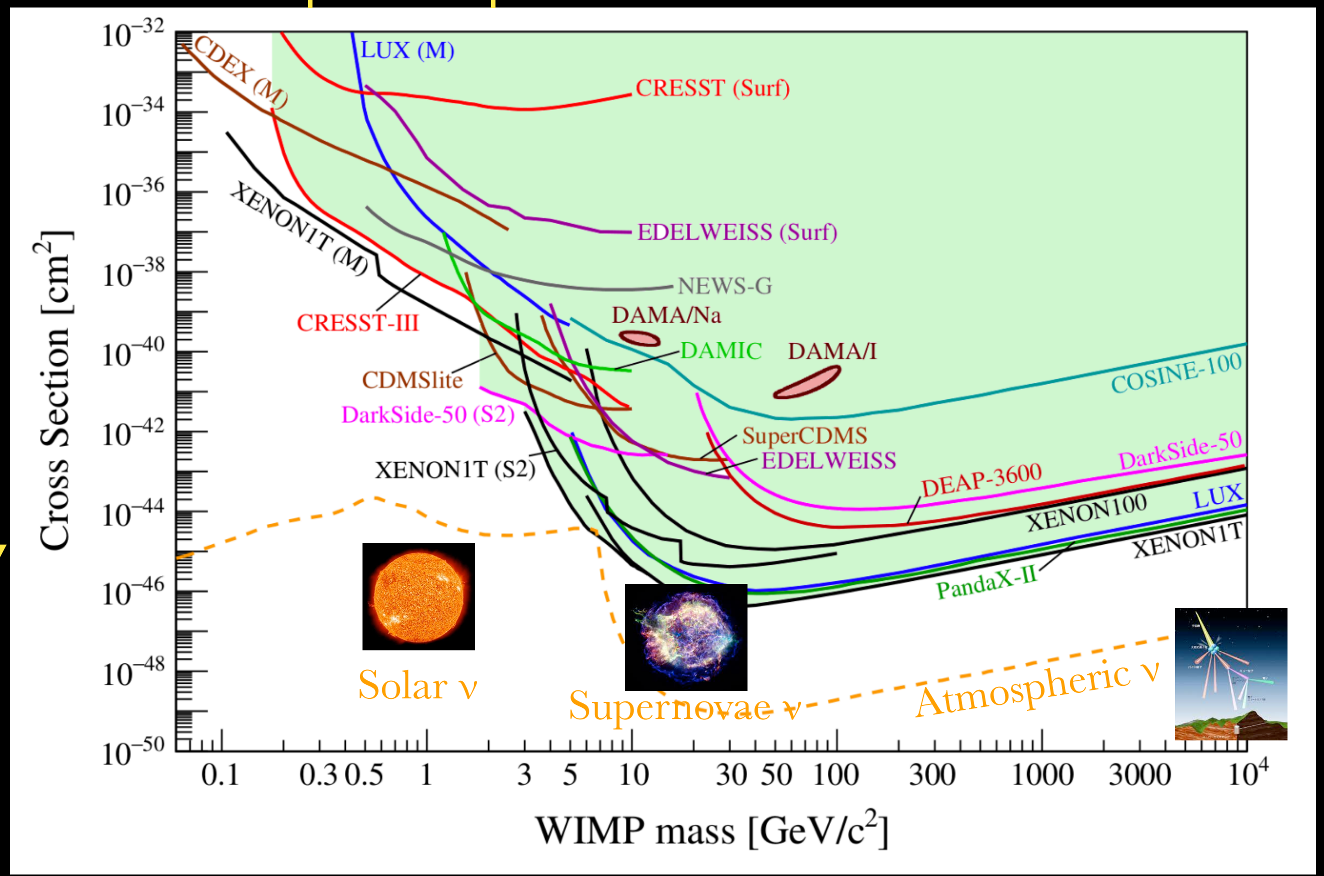


DIRECT DETECTION

Which looks for energy deposited within a detector by the DM-nuclei scattering



spin-independent WIMP-nucleon interactions



Exposure+ Background

Threshold

Direct Detection of Dark Matter – APPEC Committee Report 2021

Neutrino backgrounds at direct dark matter detection experiments

- Solar neutrinos

  W. C. Haxton, R. G. Hamish Robertson, and A. M. Serenelli, Ann. Rev. Astron. Astrophys. 51 (2013), 21

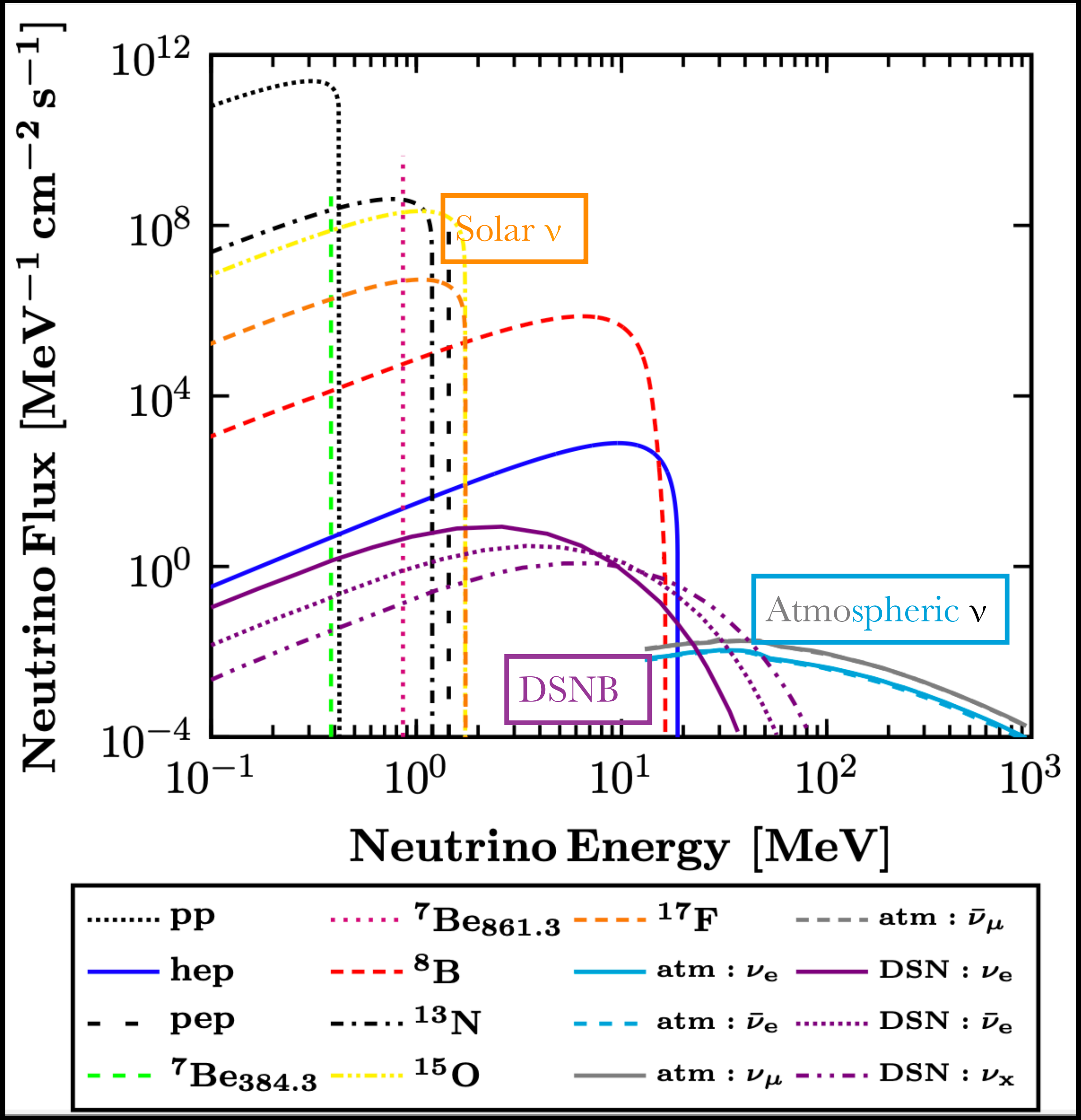
- Atmospheric neutrinos (FLUKA)

  G. Battistoni, A. Ferrari, T. Montaruli, and P. R. Sala, Astropart. Phys. 23 (2005) 526

- Diffuse Supernova Neutrinos (DSN)

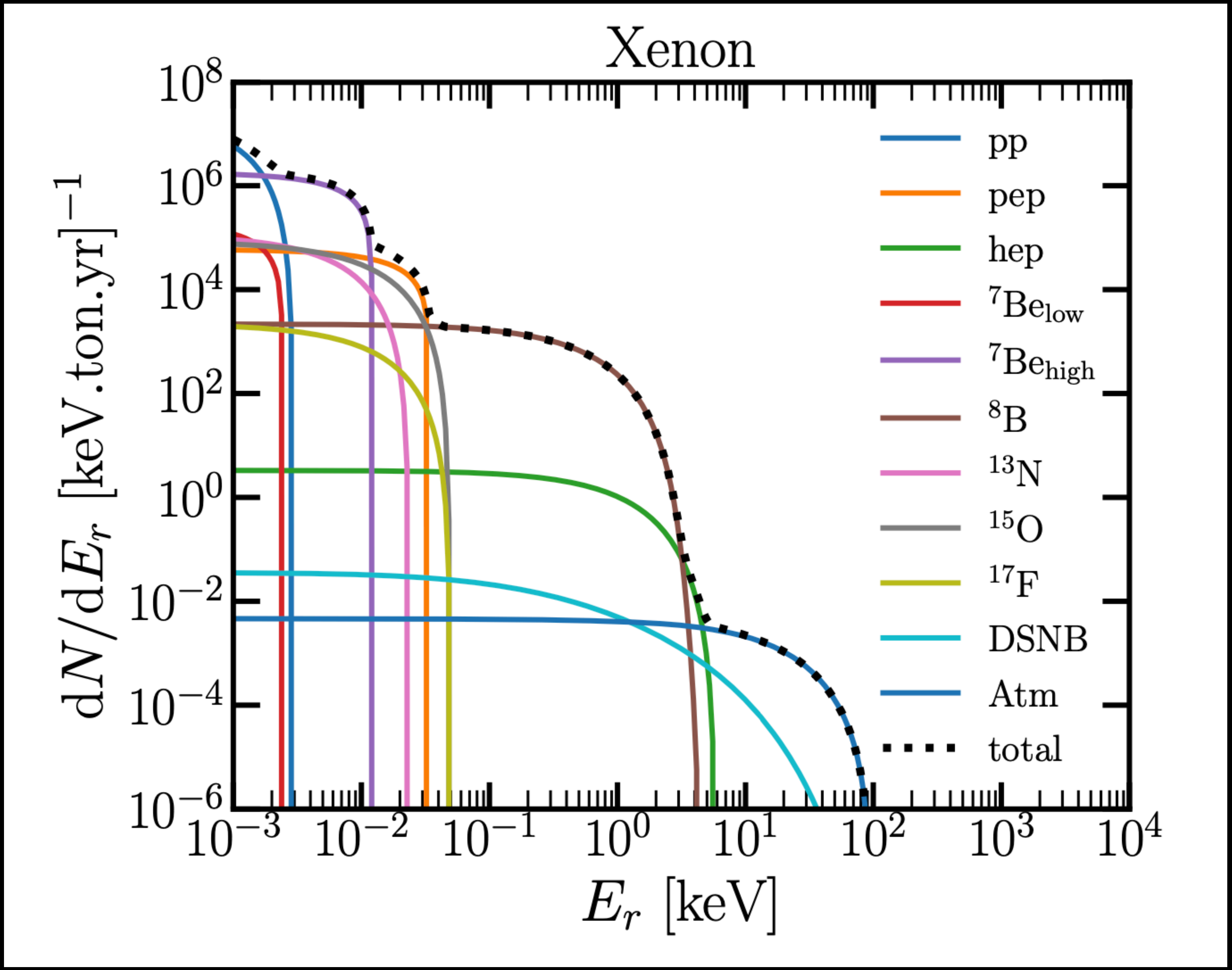
  Horiuchi, Beacom, Dwek, PR D79 (2009) 083013

Type	$E_{\nu_{\max}}$ [MeV]	Flux [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]
pp	0.423	$(5.98 \pm 0.006) \times 10^{10}$
pep	1.440	$(1.44 \pm 0.012) \times 10^{8}$
hep	18.784	$(8.04 \pm 1.30) \times 10^{3}$
$^{7}\mathrm{Be}_{\mathrm{low}}$	0.3843	$(4.84 \pm 0.48) \times 10^{8}$
$^{7}\mathrm{Be}_{\mathrm{high}}$	0.8613	$(4.35 \pm 0.35) \times 10^{9}$
$^{8}\mathrm{B}$	16.360	$(5.58 \pm 0.14) \times 10^{6}$
$^{13}\mathrm{N}$	1.199	$(2.97 \pm 0.14) \times 10^{8}$
$^{15}\mathrm{O}$	1.732	$(2.23 \pm 0.15) \times 10^{8}$
$^{17}\mathrm{F}$	1.740	$(5.52 \pm 0.17) \times 10^{6}$



Astrophysical neutrinos

Expected recoil rates from coherent neutrino-nucleus scattering on Xenon:



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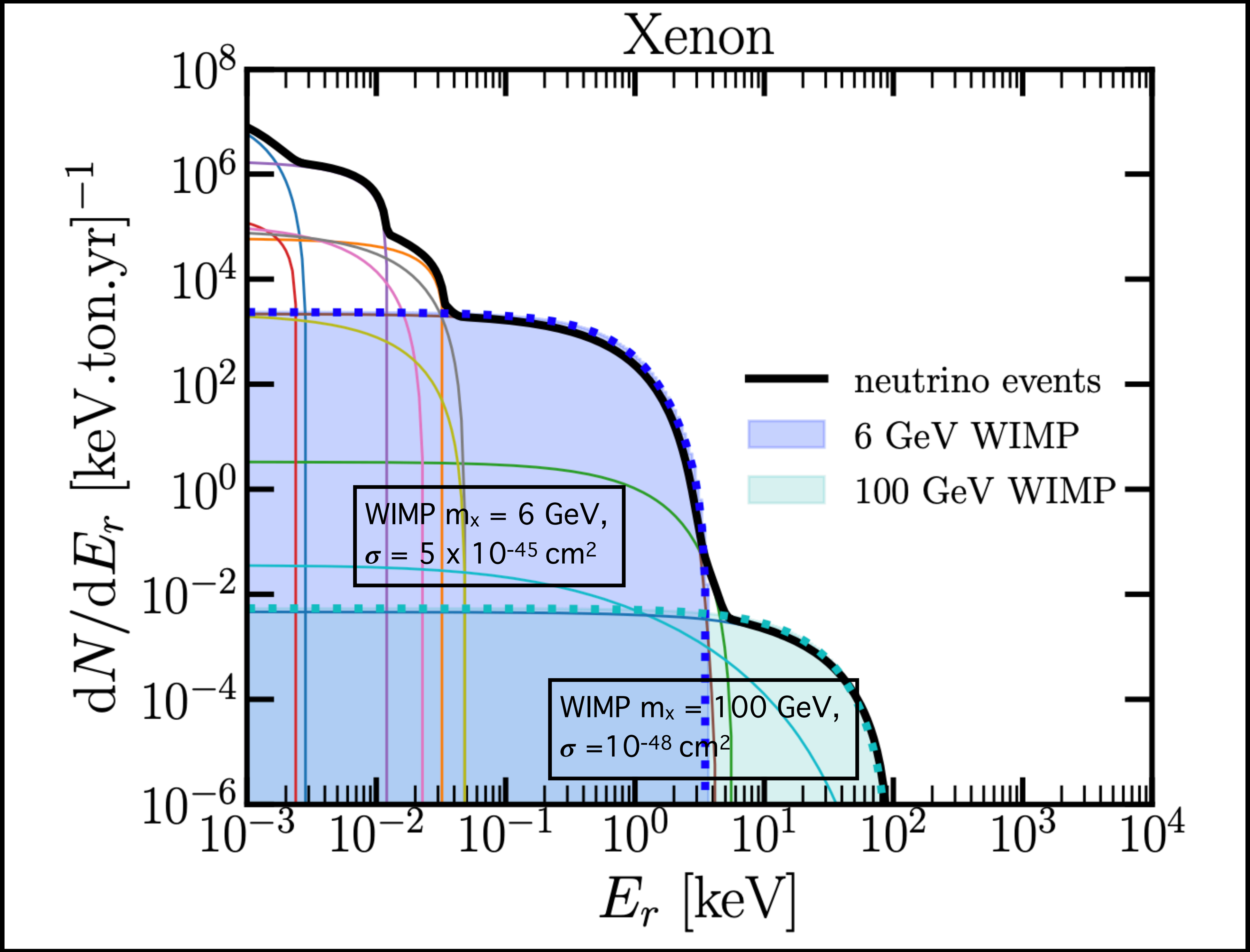

Neutrino floors (or fog)

- Neutrino backgrounds induce coherent elastic-neutrino nucleus scattering and produce nuclear recoil spectra, which can have a strong degeneracy with those expected from spin-independent WIMP interactions.

- Increasing exposure does not imply a linear improvement of sensitivities but rather a saturation of its discovery limit, typically referred to as neutrino floor.

- Neutrino floors vary depending on:
  - Astrophysical uncertainties
  - Nuclear physics uncertainties
  - Neutrino flux uncertainties
  - Non-standard interactions
  - New mediators

Strigari, New J. Phys. 11 (2009) 105011
Billard+, Phys. Rev. D89 no. 2, (2014) 023524
Ruppin+, Phys. Rev. D90 no. 8, (2014) 083510
O'Hare, Phys. Rev. D94 no. 6, (2016) 063527
Dutta+, Phys. Lett. B773 (2017) 242–246
Bertuzzo+ JHEP 04 (2017) 073
Aristizabal+, JHEP 03 (2018) 197
Papoulias+, Adv.High Energy Phys. 2018 6031362
Boehm+, JCAP 01 (2019) 043
O'Hare, 2109.03116
Snowmass 2203.08084
...

- Can be overcome with measurements of the WIMP and neutrino recoil spectra tails, directionality, measurements with different material targets and annual modulation.

WIMP discovery limits

Discovery limit: smallest WIMP cross section for which a given experiment has a 90% probability of detecting a WIMP signal at ≥ 3σ.

$$\mathcal{L}(m_\chi, \sigma_{\chi-n}, \Phi, \mathcal{P}) = \prod_{i=1}^{n_{\text{bins}}} P(N^i_{\text{Exp}}, N^i_{\text{Obs}}) \times \boxed{G(\mathcal{P}_i, \mu_{\mathcal{P}_i}, \sigma_{\mathcal{P}_i})} \times \prod_{\alpha=1}^{n_\nu} G(\phi_\alpha, \mu_\alpha, \sigma_\alpha)$$

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The profile likelihood ratio corresponds to a test against the null hypothesis H_0 (CEνNS background only) vs the alternative hypothesis H_1 (WIMP signal + CEνNS background).

- Poisson distribution $P(k, \lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$
- Gauss distribution $G(x, \mu, \sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$
- $N^i_{\text{Exp}} = N^i_\nu(\Phi_\alpha)$
- $N^i_{\text{Obs}} = \sum_\alpha N^i_\nu(\Phi_\alpha) + N^i_W$
- $\lambda(0) = \frac{\mathcal{L}_0}{\mathcal{L}_1}$ where $\mathcal{L}_0$ is the minimized function
- statistical significance: $\mathcal{Z} = \sqrt{-2 \ln \lambda(0)}$.
  e.g. $\mathcal{Z} = 3$ corresponds to 90% C.L.

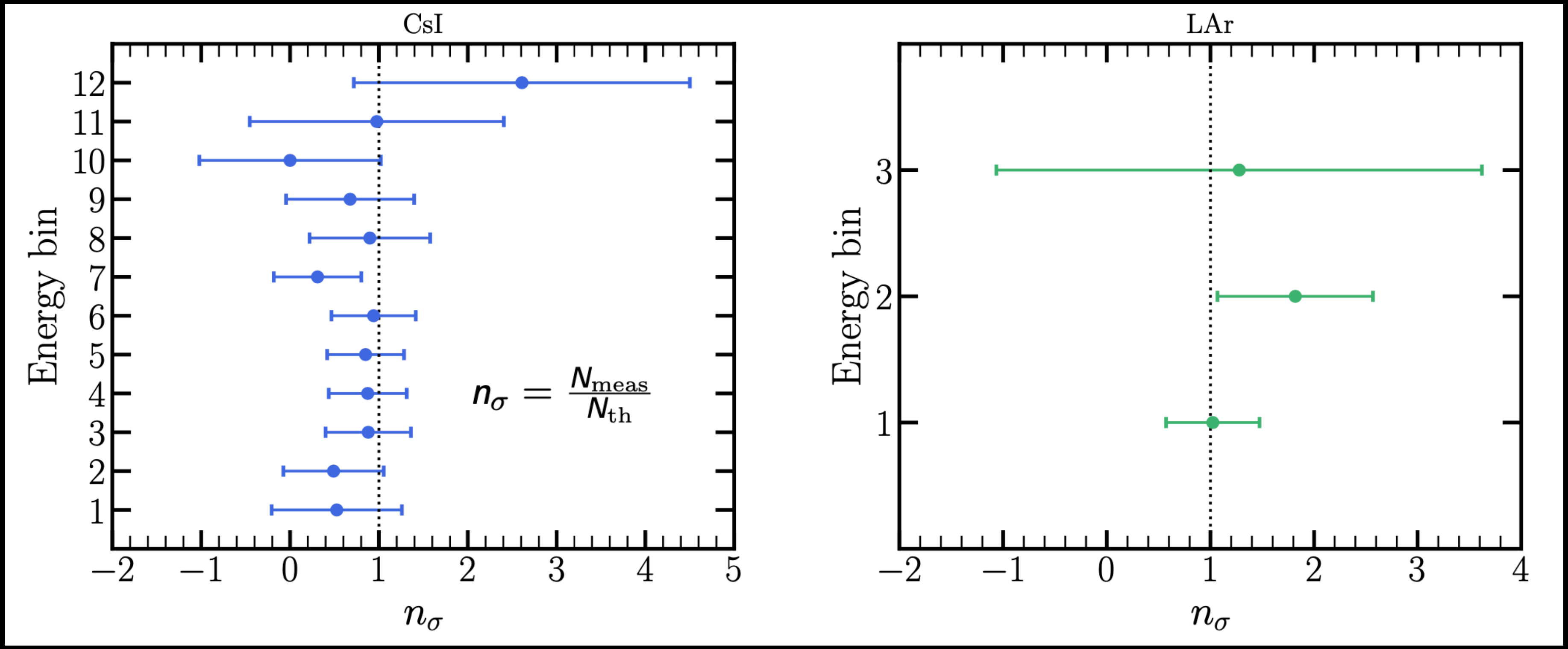
Parameter ($\mathcal{P}$)	Normalization (μ)	Uncertainty
R_n	4.78 fm	10%
$\sin^2\theta_W$	0.2387	10%

(1.a): Data-driven analysis

- Use the measured CEνNS cross section with its uncertainty. This approach encodes all possible uncertainties that the cross section can involve, independently of assumptions.

- We extract from the COHERENT CsI and LAr data the CEνNS cross section central values together with their standard deviations.

- We weigh the theoretical SM value of the CEνNS differential cross section with a multiplicative factor n_σ and use a spectral χ^2 test to fit n_σ in each recoil energy bin.



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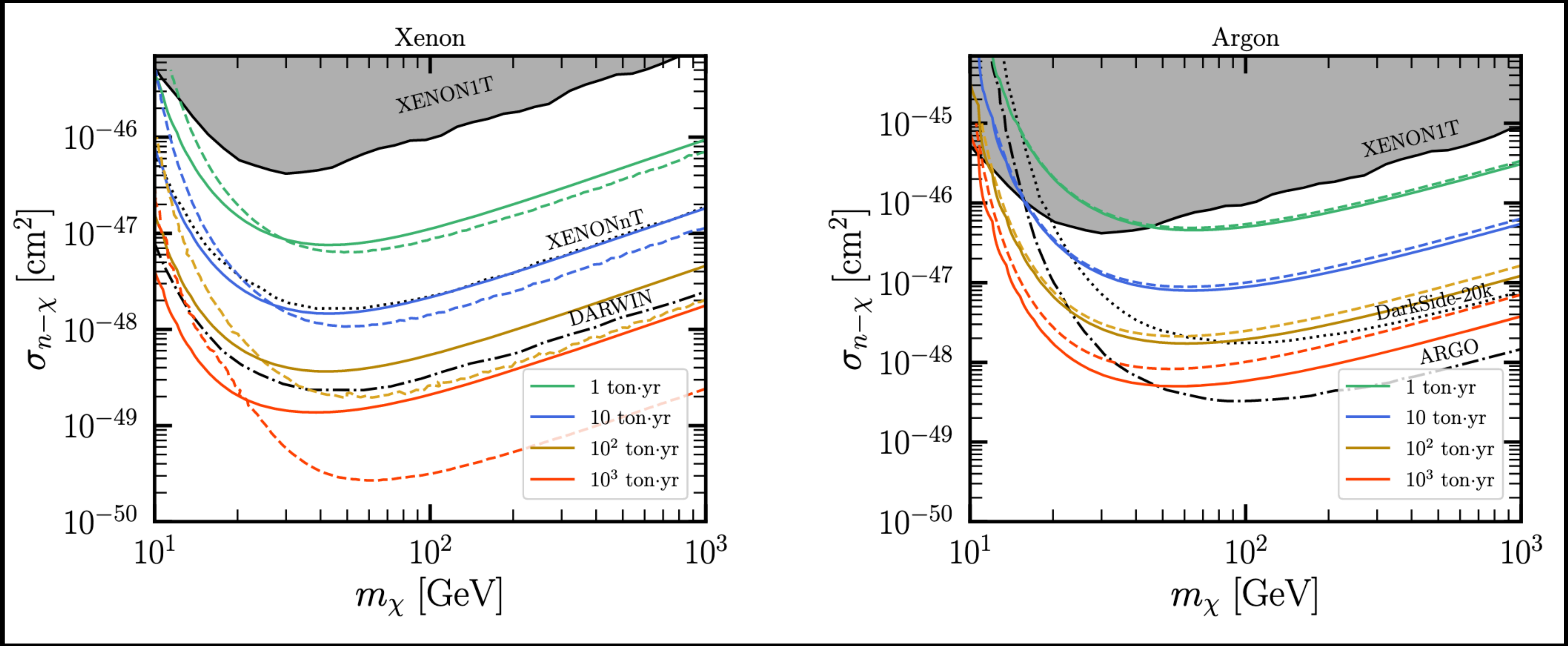
(1.a): Data-driven analysis



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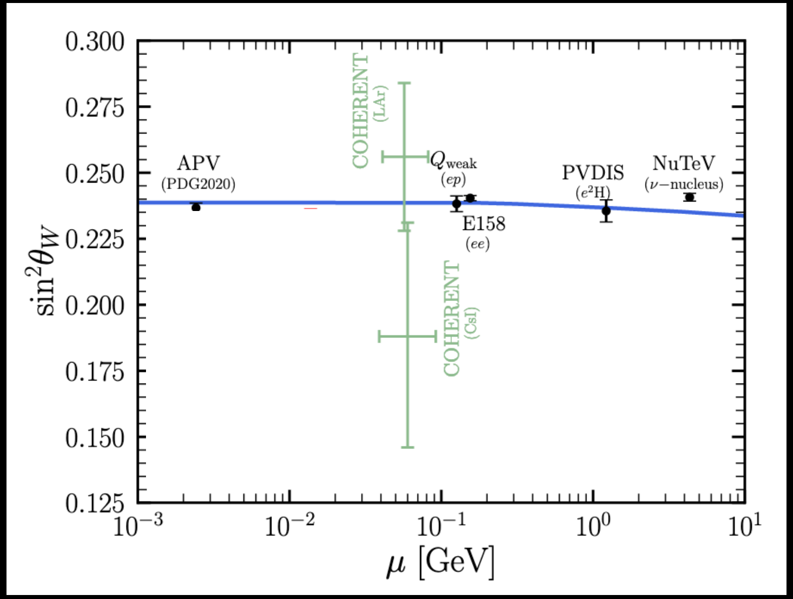
- In the analysis with CsI data, compared with the SM expectation (solid curves), WIMP discovery limits improve. The measured CEνNS cross section (central values) is smaller than the SM expectation, thus resulting in a background depletion.
- Results derived using the LAr data behave differently.

(1.b): Impact of weak mixing angle

Effects of weak mixing angle uncertainties are expected to be relevant at low WIMP masses, where solar neutrino fluxes are more abundant.

- vary around the central value: $\sin^2\theta_W = 0.2387$ (10%)

$$Q_W = \left(\tfrac{1}{2} - 2\sin^2\theta_W\right)Z - \tfrac{1}{2}N$$



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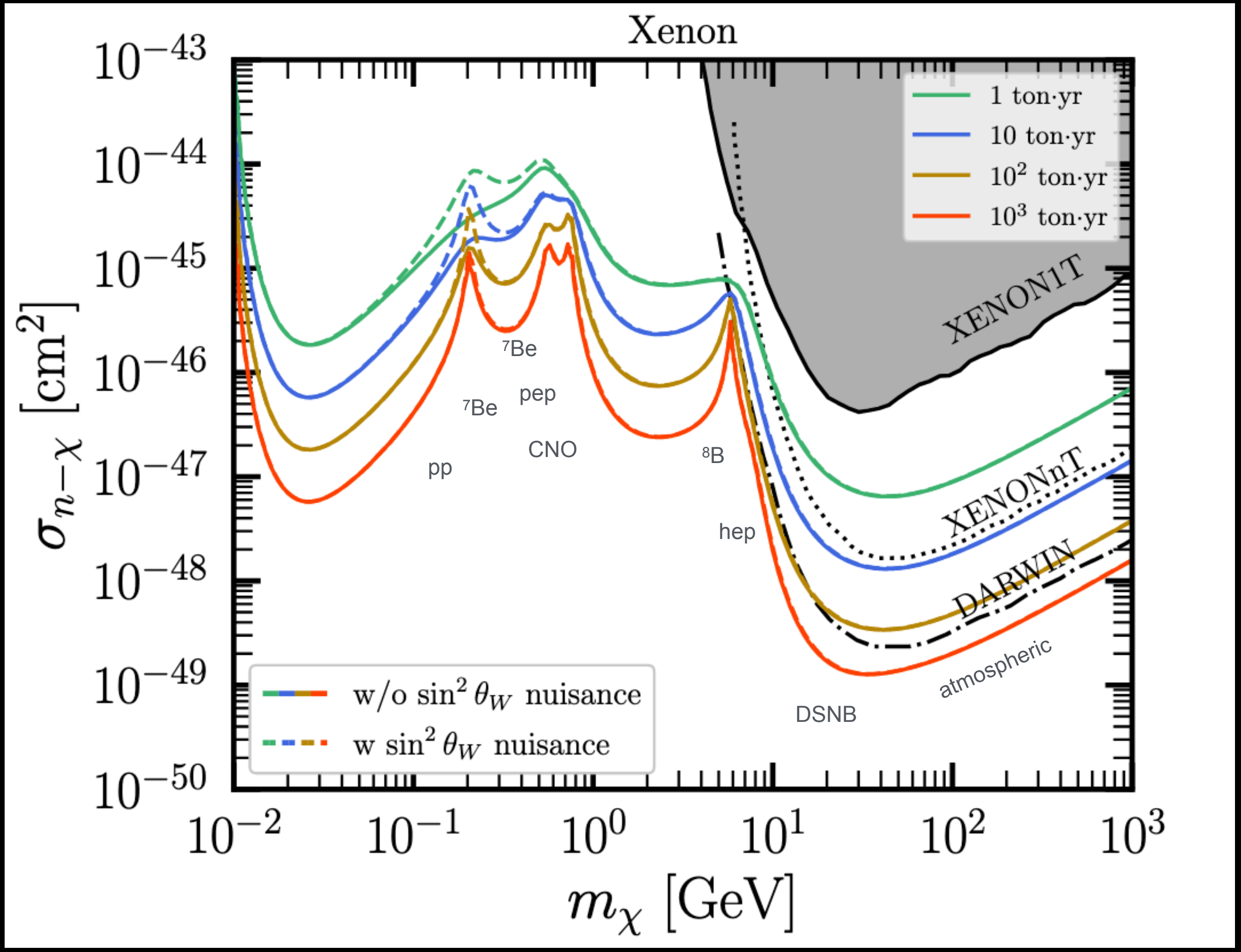

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As the weak mixing angle increases, the coherent weak charge becomes more negative.

(2.a): Light vector mediator

$$\frac{d\sigma}{dE_r} = \frac{m_N G_F}{2\pi} Q_V^2 \left(2 - \frac{m_N E_r}{E_\nu^2}\right) F^2(q)$$

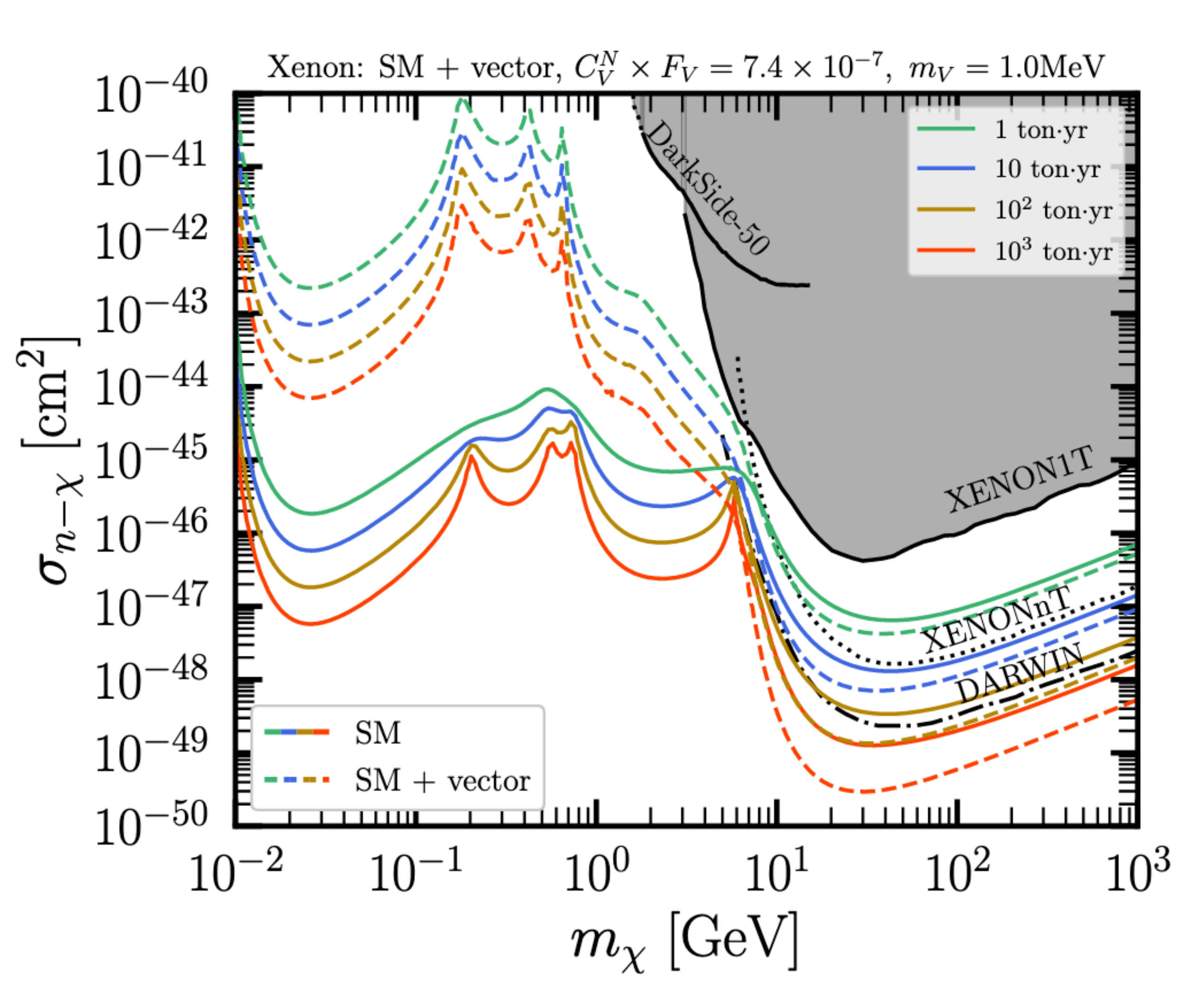
$$Q_V = Q_W + \frac{C_V^N F_V}{\sqrt{2} G_F (2 m_N E_r + m_V^2)}$$

Vector coupling to nucleus (C_V^N)

Vector coupling to neutrinos (F_V)

Cerdeño et al. JHEP 05 (2016)

- We fix the product of couplings $C^N_V F_V$ to their maximum allowed value according to COHERENT CsI data.
- Only nuisance parameters are those associated with neutrino flux normalization factors.
- At low momentum transfer the new contribution is enhanced and the neutrino background increases.
- The SM coherent weak charge is negative, while the new contribution is positive. So, as q^2 increases the new contribution becomes less important and destructively interferes with the SM term.



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(2.b): Light scalar mediator

In the presence of a scalar interaction, the CEνNS cross section consists of the sum of the SM term and

$$\frac{d\sigma_S}{dE_r} = \frac{G_F^2}{2\pi} m_N Q_S^2 \frac{m_N E_r}{2E_\nu^2} F^2(q^2)$$

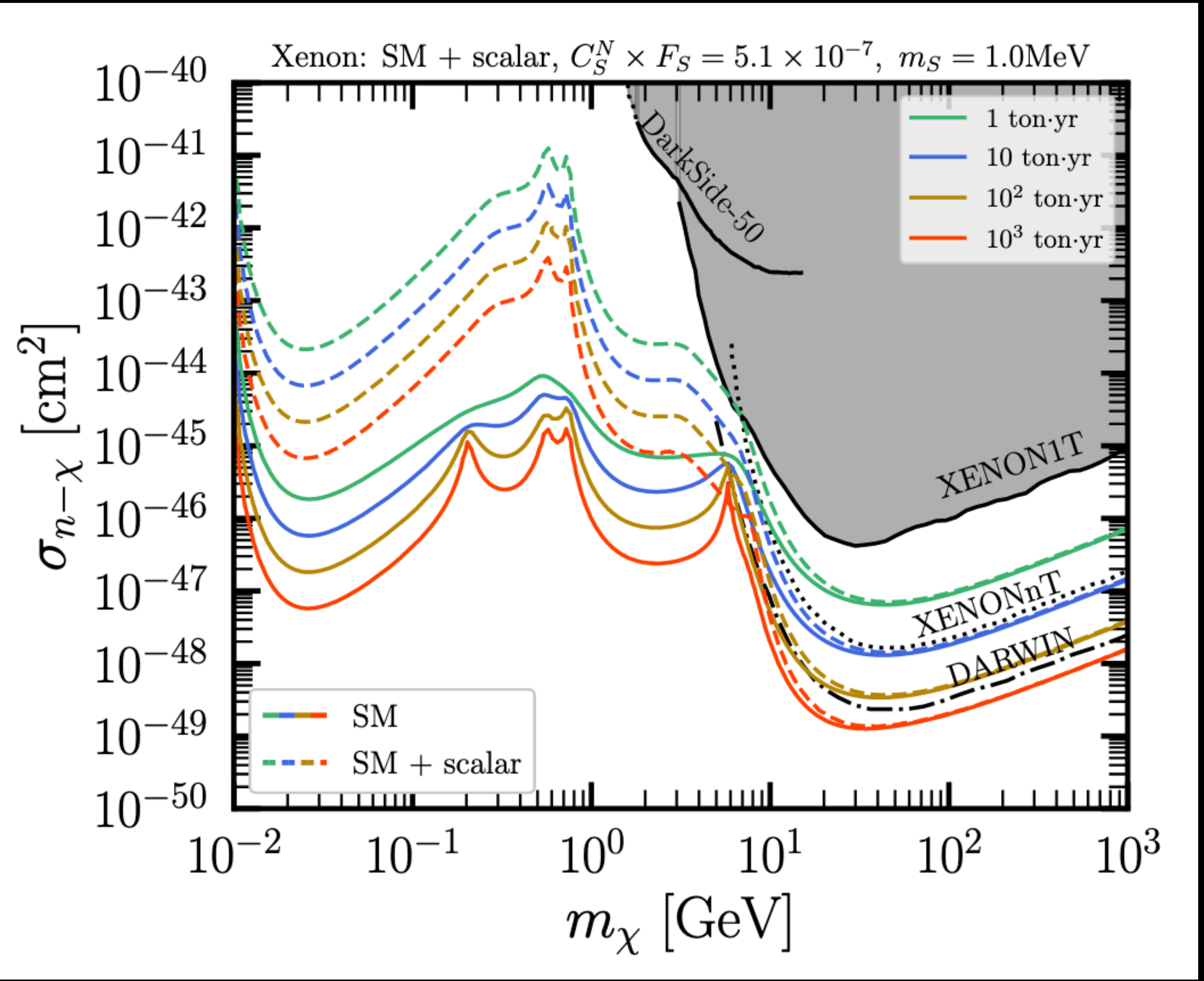
Cerdeño et al. JHEP 05 (2016)

Scalar coupling to nucleus

Scalar coupling to neutrinos

$$Q_S = \frac{C_S^N F_S}{G_F(2m_N E_r + m_S^2)}$$

- We fix the product of couplings $C^N_S F_S$ to their maximum allowed value according to COHERENT CsI data.
- The scalar contribution peaks towards the low momentum transfer region (low WIMP mass region), thus enhancing the background and worsening the discovery limit.
- Destructive interference is not possible in the scalar case (chirality flip).



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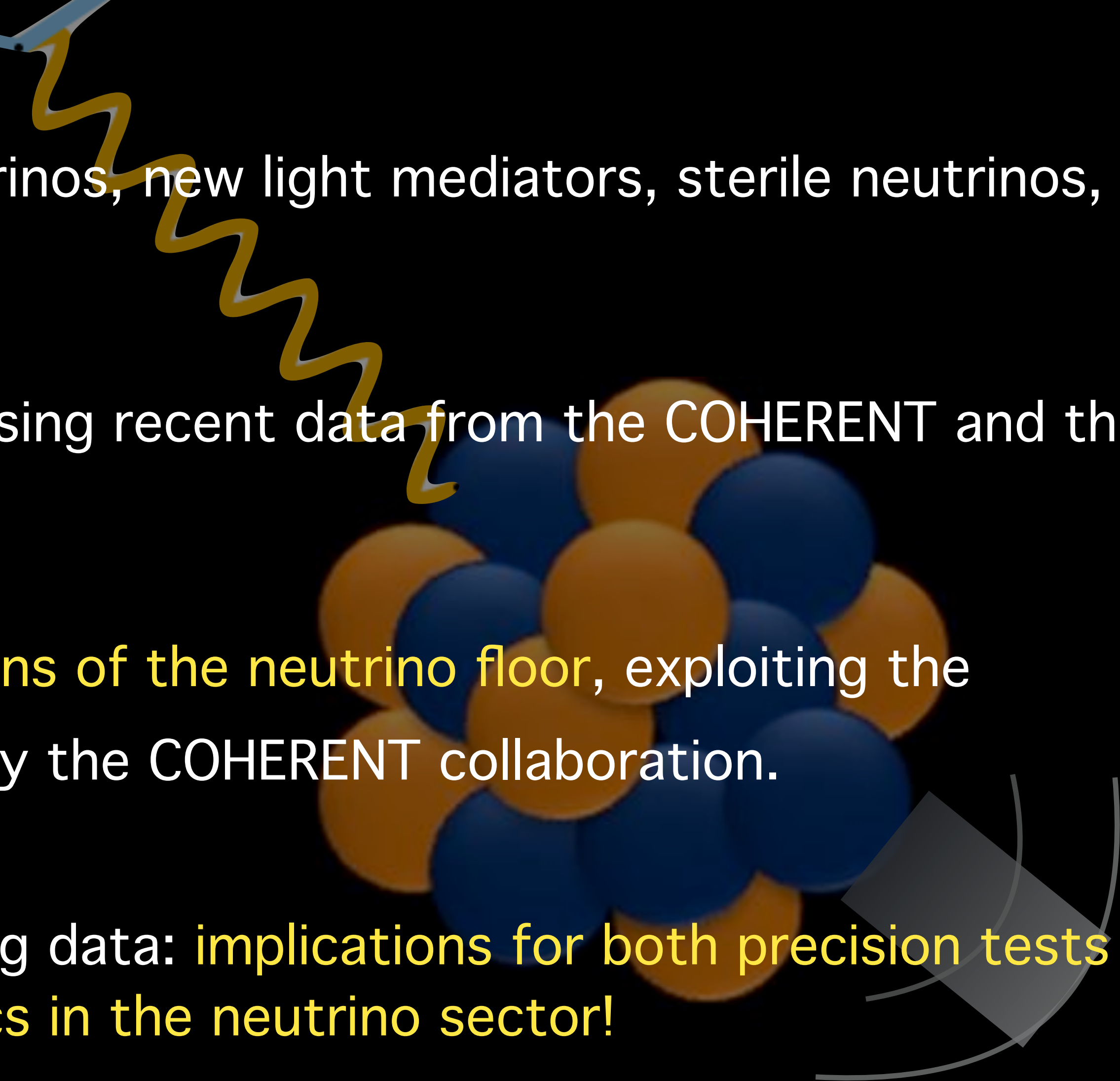
Summary

- CEνNS process:
  - coherency condition (sources: spallation source, nuclear reactors,...)
  - neutrinos scatter on a nucleus which act as a single particle
  - enhancement of cross section ($\propto N^2$)
- CEνNS extended physics potential:
  - SM (weak mixing angle), solar neutrinos, new light mediators, sterile neutrinos, neutrino floor...
- We have presented some results analysing recent data from the COHERENT and the Dresden-II experiments
- We have reconsidered possible variations of the neutrino floor, exploiting the measurements of the CEνNS process by the COHERENT collaboration.
- Wealth of information from forthcoming data: implications for both precision tests of the Standard Model and for new physics in the neutrino sector!

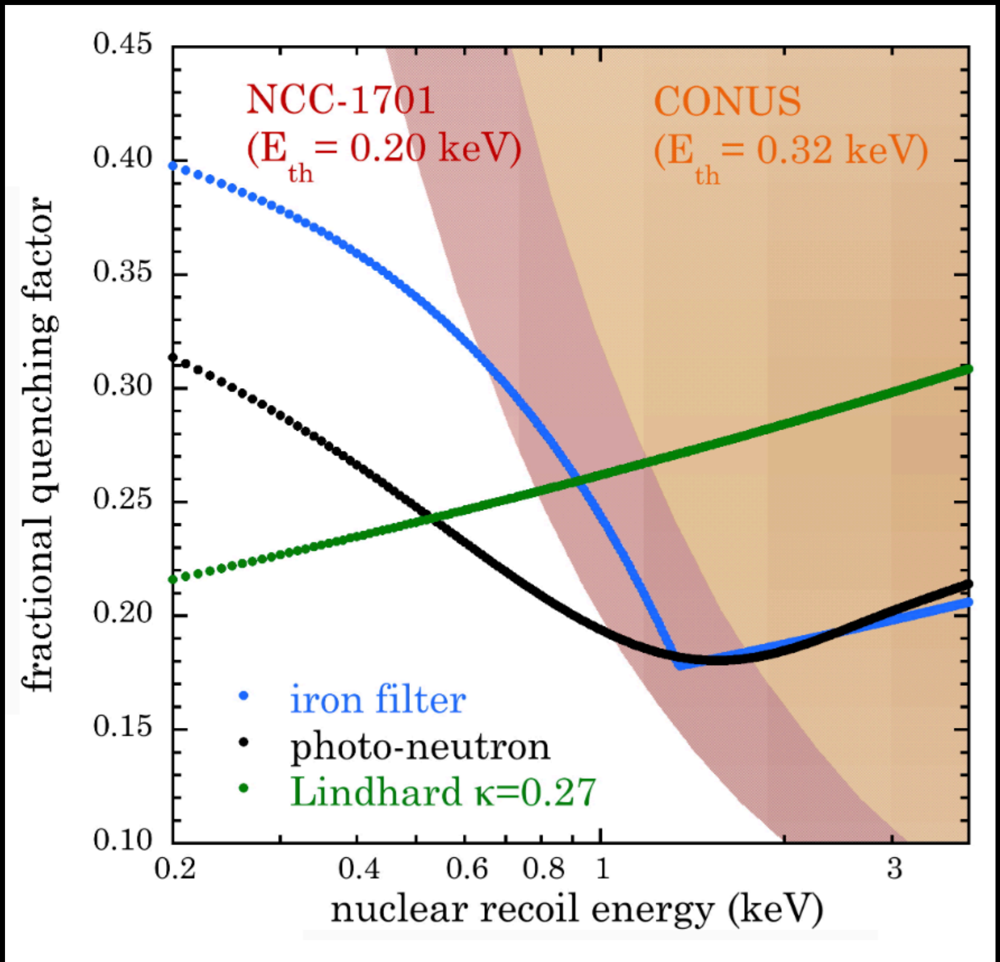



Thank
you!

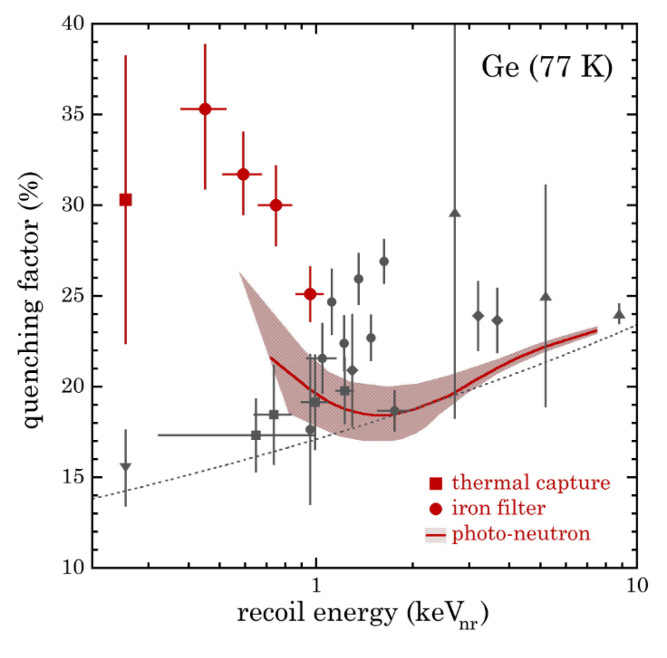
Evidence of CEνNS ? at CC-1701 (Dresden-II reactor)

The quenching factor (QF) describes the observed reduction in ionization yield produced by a nuclear recoil when compared to an electron recoil of same energy

- often not (yet) well known at low recoil energies for CEνNS
- major uncertainty!



Colaresi et al., Phys. Rev. D 104, 072003 (2021)
Colaresi et al., arXiv:2202.09672 [hep-ex]



J.I. Collar et al, Phys. Rev. D 103, 122003

$QF = E_{meas}/E_{nuclear\ recoil}$

CONUS: Direct measurement of ionization quenching factor: k=0.162+-0.004 (compatible with Lindhard)

CONUS Phys. Rev. Lett. 126, 041804

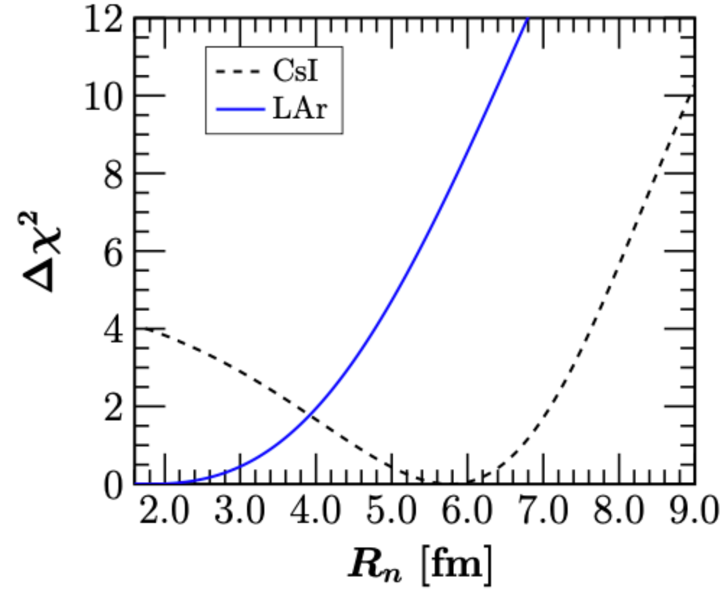
Neutrino flux components normalizations and uncertainties					
Comp.	Norm. $[\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}]$	Unc.	Comp.	Norm. $[\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}]$	Unc.
^{7}Be (0.38 MeV)	4.84×10^{8}	3%	^{7}Be (0.86 MeV)	4.35×10^{9}	3%
pep	1.44×10^{8}	1%	pp	5.98×10^{10}	0.6%
^{8}B	5.25×10^{6}	4%	hep	7.98×10^{3}	30%
^{13}N	2.78×10^{8}	15%	^{15}O	2.05×10^{8}	17%
^{17}F	5.29×10^{6}	20%	DSNB	86	50%
Atm	10.5	20%	—	—	—

Relevant WIMP related parameters			
v_0 [km/s]	v_{lab} [km/s]	v_{esc} [km/s]	ρ_0 [GeV/cm^3]
220	232	544	0.3

Parameter ($\mathcal{P}$)	Mean (μ)	Unc. (standard deviation)
$\mathcal{R}$	4.78 fm	10%
Θ	0.2387	10%

Phenomenological form factors (Klein-Nystrand)

[Miranda et al. JHEP 05 (2020) 130]



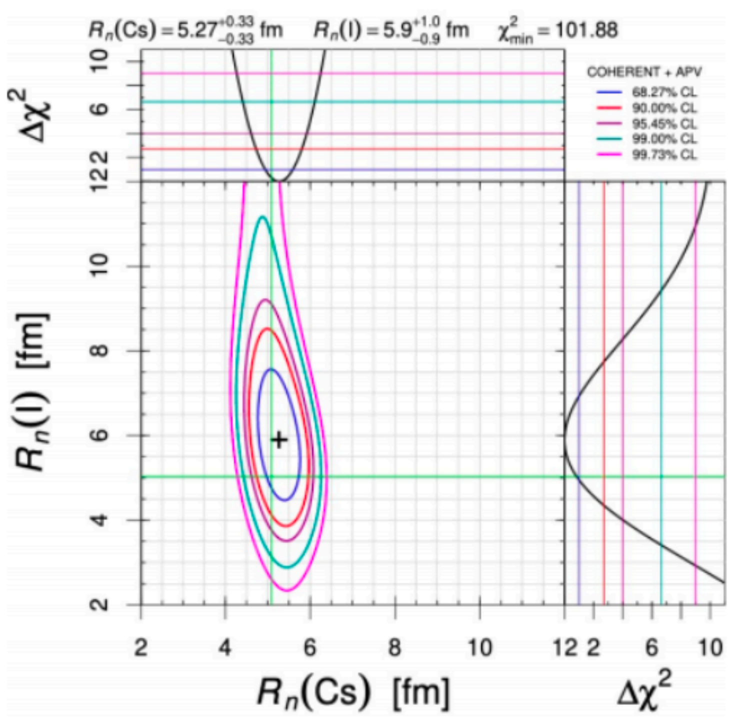
Follows from the convolution of a Yukawa potential with range $a_k = 0.7$ fm over a Woods-Saxon distribution, approximated as a hard sphere with radius R_A.

$$F_{\text{KN}} = 3\frac{j_1(QR_A)}{qR_A}\left[1 + (Qa_k)^2\right]^{-1}$$

The rms radius is: $\langle R^2 \rangle_{\text{KN}} = 3/5R_A^2 + 6a_k^2$

[Klein, Nystrand, PRC 60 (1999) 014903]

[Cadeddu et al., arXiv:2102.06153]



- **CEvNS data provides:** a data driven determination of the neutron rms radius
- **COHERENT (CsI) + APV (Cs):** can disentangle the Cs and I contributions

Slide from D. Papoulias

WIMP-nucleus scattering

weakly interacting massive particles (WIMPs)

Differential event rate as a function of E_r

$$\frac{dR_W}{dE_r} = \varepsilon \frac{\rho_0 \sigma_{\rm SI}(q)}{2 m_\chi \mu^2} \int_{|\boldsymbol{v}|>v_{\rm min}} d^3 v \, \frac{f(\boldsymbol{v})}{v}$$

[Lewin and Smith: Astropart. Phys. 6 (1996)]

Slide from D. Papoulias

- $\rho_0 = 0.3\ \mathrm{GeV/cm^2}$ local Halo DM density
- $\sigma_{\rm SI}(q) = \frac{\mu^2}{\mu_n^2} \left[Z F_p(q) + (A - Z) F_n(q) \right]^2 \sigma_{\chi - n}$
  Spin-independent WIMP-nucleus scattering
- m_χ: WIMP mass
- $\mu = m_\chi m_N / (m_\chi + m_N)$: WIMP-nucleus reduced mass
- $f(v) = \begin{cases} \frac{1}{N_{\rm esc}} \left(\frac{3}{2\pi \sigma_v^2} \right)^{3/2} e^{-3\boldsymbol{v}^2/2\sigma_v^2} & \text{for} \quad v < v_{\rm esc} \\ 0 & \text{for} \quad v > v_{\rm esc} \end{cases}$ (Maxwell distribution)

Neutrino Generalised Interactions (NGI)

- NSI are a subset of a larger set of neutrino-quark interactions: Neutrino Generalised Interactions (NGI)
- all Lorentz invariant non-derivative interactions of neutrinos with first generation quarks

$$\mathscr{L}_{\rm eff}^{\rm NGI} = \frac{G_F}{\sqrt{2}} \sum_X \bar{\nu}\Gamma^X \nu\, \bar{q}\Gamma_X \left(C_X^q + i\gamma_5\, D_X^q\right) q$$

Kayser et al. Phys. Rev. D 20, 87
Lindner et al. JHEP03(2017)097

$$\Gamma_X = \{\mathbb{I}, i\gamma_5, \gamma_\mu, \gamma_5\gamma_\mu, \sigma_{\mu\nu}\}$$

$$\mathscr{L}_S \sim (\bar{\nu}\nu)\left[\bar{q}\left(C_S^q + i\gamma_5 D_S^q\right) q\right]$$

$$\mathscr{L}_P \sim (\bar{\nu}\gamma_5\nu)\left[\bar{q}\left(\gamma_5 C_P^q + i D_P^q\right) q\right]$$

$$\mathscr{L}_V \sim (\bar{\nu}\gamma^\mu\nu)\left[\bar{q}\left(\gamma_\mu C_V^q + i\gamma_\mu\gamma_5 D_V^q\right) q\right]$$

$$\mathscr{L}_A \sim (\bar{\nu}\gamma^\mu\gamma_5\nu)\left[\bar{q}\left(\gamma_\mu\gamma_5 C_A^q + i\gamma_\mu D_A^q\right) q\right]$$

$$\mathscr{L}_T \sim (\bar{\nu}\sigma^{\mu\nu}\nu)\left[\bar{q}\left(\sigma_{\mu\nu} C_T^q + i\sigma_{\mu\nu}\gamma_5 D_T^q\right) q\right]$$

- Constrain dominant spin-independent contributions (C^q_X)
- Neglect Pseudoscalar and Axial interactions (spin-dependent: $Z_\uparrow - Z_\downarrow$, $N_\uparrow - N_\downarrow$)

Freedman et al. Ann. Rev. Nucl. Part. Sci. 27 (1977)

From quark to nuclear currents

- To compute the CEνNS cross section induced by the NGI we assume a fermion nuclear ground state with spin J = 1/2.

$$\frac{d\sigma^a(q^2=0)}{dE_r} = \frac{G_F^2}{4\pi} m_{N_a} N_a^2 \left[\xi_S^2 \frac{E_r}{E_r^{\max}} + \xi_V^2 \left(1 - \frac{E_r}{E_r^{\max}} - \frac{E_r}{E_\nu}\right) + \xi_T^2 \left(1 - \frac{E_r}{2E_r^{\max}} - \frac{E_r}{E_\nu}\right) - R\frac{E_r}{E_\nu} \right]$$

$$\xi_S^2 = \frac{C_S^2 + D_P^2}{N^2}\,, \quad \xi_V^2 = \frac{C_V^2 + D_A^2}{N^2}\,, \quad \xi_T^2 = 8\frac{C_T^2}{N^2}\,, \quad R = 2\frac{C_S C_T}{N^2}$$

- ν – N coefficients are written as follows

$$C_S = Z \sum_{q=u,d} C_S^{(q)} \frac{m_p}{m_q} f_{T_q}^p + (A-Z) \sum_{q=u,d} C_S^{(q)} \frac{m_n}{m_q} f_{T_q}^n\,,$$

$$C_V = Z\left(2C_V^u + C_V^d\right) + (A-Z)\left(C_V^u + 2C_V^d\right)\,,$$

$$C_T = Z\left(\delta_u^p C_T^u + \delta_d^p C_T^d\right) + (A-Z)\left(\delta_u^n C_T^u + \delta_d^n C_T^d\right)\,.$$

e.g. Dent et al. Phys. Rev. D92 (2015) 063515

From quark to nuclear currents

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$$\frac{d\sigma^a(q^2=0)}{dE_r} = \frac{G_F^2}{4\pi} m_{N_a} N_a^2 \left[\xi_S^2 \frac{E_r}{E_r^{\max}} + \xi_V^2 \left(1 - \frac{E_r}{E_r^{\max}} - \frac{E_r}{E_\nu}\right) + \xi_T^2 \left(1 - \frac{E_r}{2E_r^{\max}} - \frac{E_r}{E_\nu}\right) - R\frac{E_r}{E_\nu} \right]$$

- STEP I: $\mathcal{O}_q \xrightarrow{\text{step (I)}} \mathcal{O}_n$ we calculate quark currents in nucleons according to

SCALAR: f_Tq: fraction of the nucleon mass "carried" by a particular quark flavor.
For vector currents, the coefficients Nnq can be understood essentially as the number of quarks within the nucleon, while for tensor currents δnq represents a tensor charge

$$\langle n(p_f)|\bar{q}\,q|n(p_i)\rangle = \frac{m_n}{m_q} f_{T_q}\,\bar{n}\,n\,,$$
$$\langle n(p_f)|\bar{q}\gamma^\mu q|n(p_i)\rangle = \mathcal{N}_q^n\,\bar{n}\,\gamma^\mu\,n\,,$$
$$\langle n(p_f)|\bar{q}\,\sigma^{\mu\nu}\,q|n(p_i)\rangle = \delta_q^n\,\bar{n}\,\sigma^{\mu\nu}\,n\,.$$

- STEP II: $\mathcal{O}_n \xrightarrow{\text{step (II)}} \mathcal{O}_N$ we evaluate the correlators of nucleonic currents in nuclei, which involve nuclear form factors:

$$\langle N(k_2)|\bar{n}\,n|N(p_2)\rangle = \bar{N}\,N F(q^2)$$

Helm form factor

$$\langle N(k_2)|\bar{n}\gamma^\mu n|N(p_2)\rangle = \bar{N}\left(\gamma^\mu F(q^2) + \frac{\sigma^{\mu\nu}q_\nu}{2m_N}F_1(q^2)\right)N$$

$$\langle N(k_2)|\bar{n}\,\sigma^{\mu\nu}\,n|N(p_2)\rangle = \bar{N}\left(i\sigma^{\mu\nu}F(q^2) - \frac{\gamma^\mu q^\nu - \gamma^\nu q^\mu}{2m_N}F_2(q^2) - \frac{K^\mu q^\nu - K^\nu q^\mu}{2m_N^2}F_3(q^2)\right)N$$

e.g. Dent et al. Phys. Rev. D92 (2015) 063515

Neutrino Magnetic and Electric Moments

Slide from C. Giunti

- Effective dimension-5 Lagrangian:

$$\mathcal{L}_{\text{mag}} = \frac{1}{2} \sum_{k,j=1}^{\mathcal{N}} \overline{\nu_{Lk}} \, \sigma^{\alpha\beta} \left(\mu_{kj} + \varepsilon_{kj} \gamma_5 \right) N_{Rj} \, F_{\alpha\beta} + \text{H.c.}$$

- $\mathcal{N} = 3$, $N_{Rj} = \nu_{Rj}$, and $\Delta L = 0$ $\Longrightarrow$ Dirac neutrinos with diagonal and off-diagonal (transition) magnetic and electric moments.
Simplest SM extension:

$$\mu_{kk}^{\text{D}} \simeq 3.2 \times 10^{-19} \mu_{\text{B}} \left(\frac{m_k}{\text{eV}} \right)$$

Strongly suppressed by small m_k!

- $\mathcal{N} = 3$ and $N_{Rj} = \nu_{Lj}^c$ $\Longrightarrow$ Majorana neutrinos with transition magnetic and electric moments only

- $\mathcal{N} > 3$ $\Longrightarrow$ active + sterile Dirac ($\Delta L = 0$) or Majorana neutrinos

"neutrino dipole portal" or "neutrino magnetic moment portal"

New neutrino interactions

Light tensor mediator

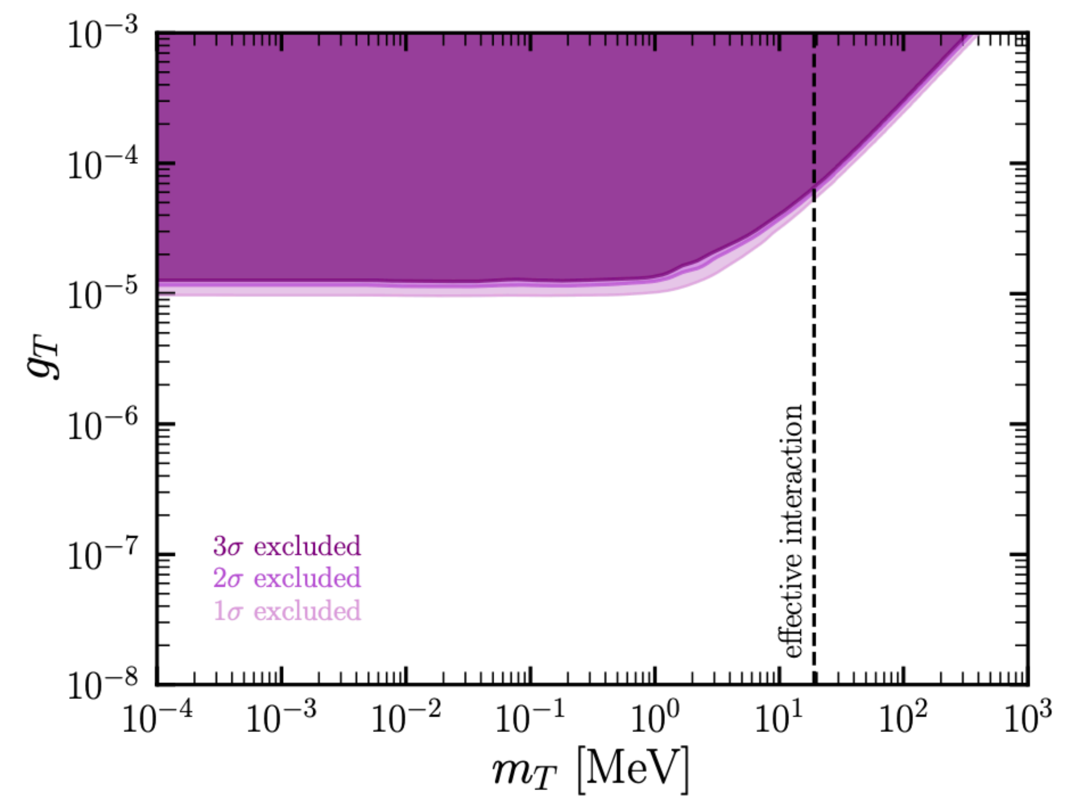
$$\xi_T^2 = 4C_T^2$$

$$\left.\frac{d\sigma}{dE_r}\right|_{\text{NGI}} = \frac{G_F^2}{2\pi} m_N F^2(q^2) \left[\xi_S^2 \frac{2E_r}{E_r^{\max}} + \xi_V^2 \left(2 - \frac{2E_r}{E_r^{\max}}\right) + \xi_T^2 \left(2 - \frac{E_r}{E_r^{\max}}\right)\right]$$

$$C_X = \frac{1}{\sqrt{2}G_F} \frac{f_X \overline{C}_X}{2m_N E_r + m_X^2}$$

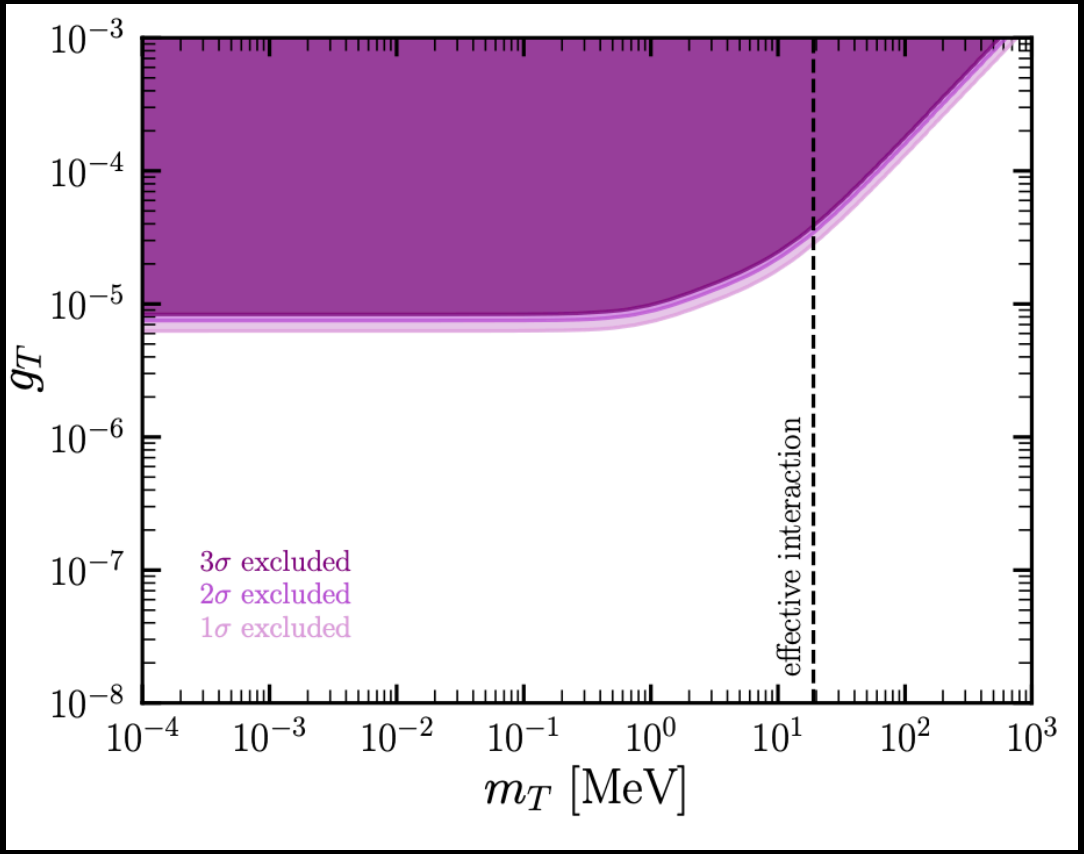
$$\overline{C}_T = Z(\delta_u^p g_T^u + \delta_d^p g_T^d) + (A-Z)(\delta_u^n g_T^u + \delta_d^n g_T^d)$$

Dresden-II (Ge) - mod. Lindhard



Aristizabal, VDR, Papoulias arXiv:2203.02414

Dresden-II (Ge) - iron filter



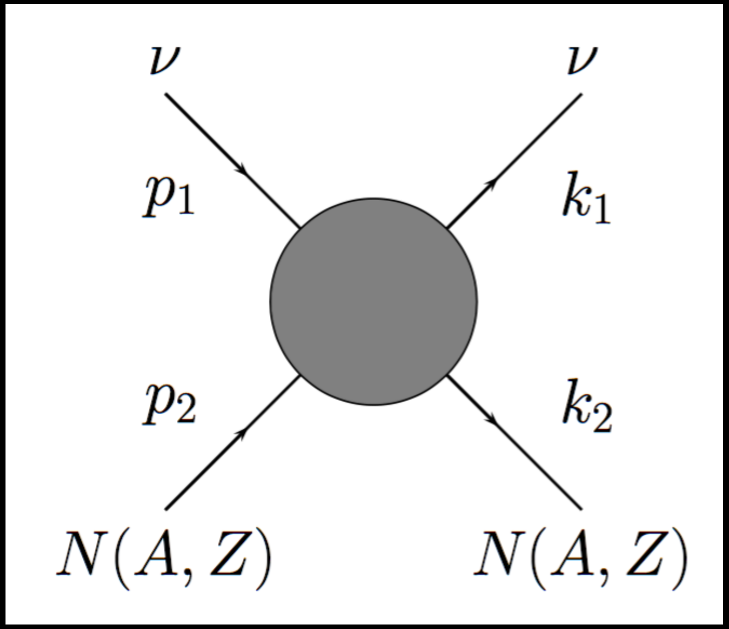
Aristizabal, VDR, Papoulias arXiv:2203.02414

NGI and CEvNS

- Cross section parameterised in terms of nuclear currents: Scalar, Vector and Tensor

$$\frac{d\sigma^a(q^2=0)}{dE_r} = \frac{G_F^2}{4\pi} m_{N_a} N_a^2 \left[\xi_S^2 \frac{E_r}{E_r^{\max}} + \xi_V^2 \left(1 - \frac{E_r}{E_r^{\max}} - \frac{E_r}{E_\nu}\right) + \xi_T^2 \left(1 - \frac{E_r}{2E_r^{\max}} - \frac{E_r}{E_\nu}\right) - R\frac{E_r}{E_\nu} \right]$$

$$E_r^{\max} \simeq 2E_\nu^2/m_{N_a}$$



- Single-parameter scenario
- Two-parameter scenario

Lindner et al. JHEP03(2017)097
D. Aristizabal, VDR, N. Rojas, Phys.Rev. D98 (2018) 075018

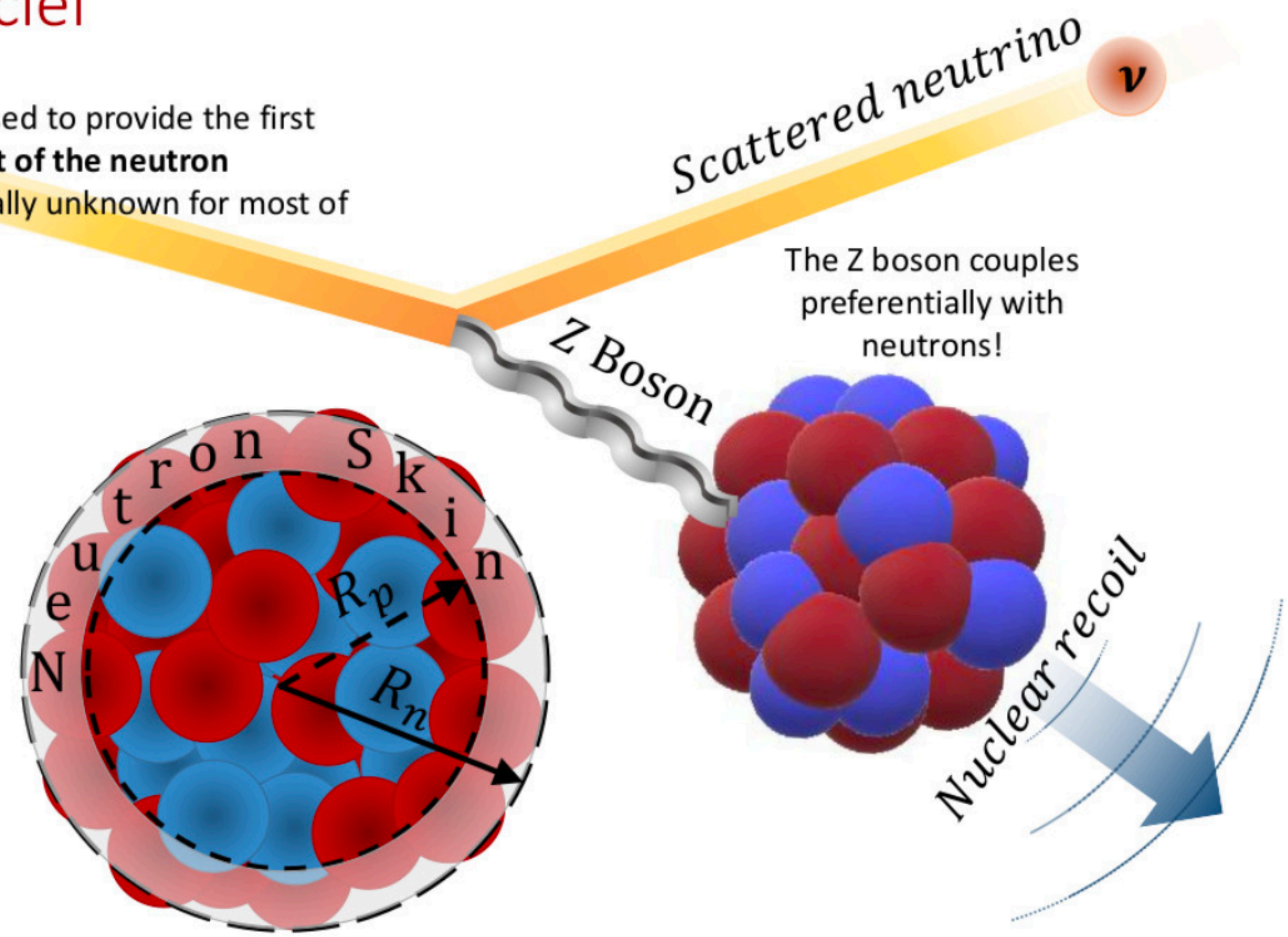
Nuclear rms radius

The CEnNS process as unique probe of the neutron density distribution of nuclei

The CEnNS process itself can be used to provide the first **model independent measurement of the neutron distribution radius**, which is basically unknown for most of the nuclei.

Even if it sounds strange, spatial distribution of neutrons inside nuclei is basically unknown!

The rms neutron distribution radius Rn and the difference between Rn and the rms radius Rp of the proton distribution (the so-called "**neutron skin**")



8

slide from: M. Cadeddu @ NuFact 2018

WIMP discovery limits

Discovery limit: smallest WIMP cross section for which a given experiment has a 90% probability of detecting a WIMP signal at ≥ 3σ.

$$\mathcal{L}(m_\chi, \sigma_{\chi-n}, \Phi, \mathcal{P}) = \prod_{i=1}^{n_{\text{bins}}} P(N^i_{\text{Exp}}, N^i_{\text{Obs}}) \times \prod_{\alpha=1}^{n_\nu} G(\phi_\alpha, \mu_\alpha, \sigma_\alpha)$$

Billard, Strigari, Figueroa-Feliciano PRD 89(2014)

The profile likelihood ratio corresponds to a test against the null hypothesis H_0 (CEvNS background only) vs the alternative hypothesis H_1 (WIMP signal + CEvNS background).

- Poisson distribution $P(k,\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$
- Gauss distribution $G(x,\mu,\sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$
- $N^i_{\text{Exp}} = N^i_\nu(\Phi_\alpha)$
- $N^i_{\text{Obs}} = \sum_\alpha N^i_\nu(\Phi_\alpha) + N^i_W$
- $\lambda(0) = \frac{\mathcal{L}_0}{\mathcal{L}_1}$ where $\mathcal{L}_0$ is the minimized function
- statistical significance: $\mathcal{Z} = \sqrt{-2\ln\lambda(0)}$.
  e.g. $\mathcal{Z} = 3$ corresponds to 90% C.L.

Neutrino flux components normalizations and uncertainties

Comp.	Norm. [$\text{cm}^{-2}\cdot\text{s}^{-1}$]	Unc.	Comp.	Norm. [$\text{cm}^{-2}\cdot\text{s}^{-1}$]	Unc.
^{7}Be (0.38 MeV)	4.84×10^8	3%	^{7}Be (0.86 MeV)	4.35×10^9	3%
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^{17}F	5.29×10^6	20%	DSNB	86	50%
Atm	10.5	20%	—	—	—

Billard+,PRD 89 n2 (2014) 023524
Ruppin+, Phys. Rev. D90 no. 8, (2014) 083510
O'Hare+, PRD 92 (2015) 063518
O'Hare, Phys. Rev. D94 no. 6, (2016) 063527
Gonzalez-Carcía+, JHEP 07 (2018) 019
....

Extraction of CEvNS cross section from COHERENT data

$$\sigma^i_{\rm meas} = n^i_\sigma\, \sigma^i_{\rm th}$$

CsI

$$\chi_i^2 = \left[\frac{N^i_{\rm exp} - (1+\alpha)N^i_{\rm meas}(n^i_\sigma) - (1+\beta)B^i_{0n}}{\sigma^i_{\rm stat}}\right]^2 + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2, \qquad \text{(A1)}$$

LAr

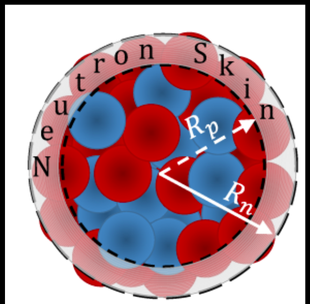
$$\chi_i^2 = \frac{\left(N^i_{\rm exp} - \alpha N^i_{\rm meas}(n^i_\sigma) - \beta B^i_{\rm PBRN} - \gamma B^i_{\rm LBRN}\right)^2}{\left(\sigma^i_{\rm exp}\right)^2 + \left[\sigma_{\rm BRNES}\left(B^i_{\rm PBRN} + B^i_{\rm LBRN}\right)\right]^2} + \left(\frac{\alpha-1}{\sigma_\alpha}\right)^2 + \left(\frac{\beta-1}{\sigma_\beta}\right)^2 + \left(\frac{\gamma-1}{\sigma_\gamma}\right)^2.$$

α and β are nuisance parameters which account for the uncertainty on the rate with σ_α = 28% and on the prompt neutron background B_{0n} with σ_β = 25%, respectively. The statistical uncertainty is defined as $\sigma_{stat} = \sqrt{N^i_{exp} + B^i_{0n} + 2B_{iss}}$, where B_{iss} denotes the steady state background.

BRNES corresponds to the Beam Related Neutron Energy Shape, while PBRN (LBRN) represents the Prompt (Late) Beam-Related Neutron Background data with σ_β = 32% (σ_γ = 100%)

(1.c): Impact of nuclear form factor

Differences between proton and neutron distributions are expected to be substantial for neutron-rich nuclei → impact on the values of the nuclear form factor.



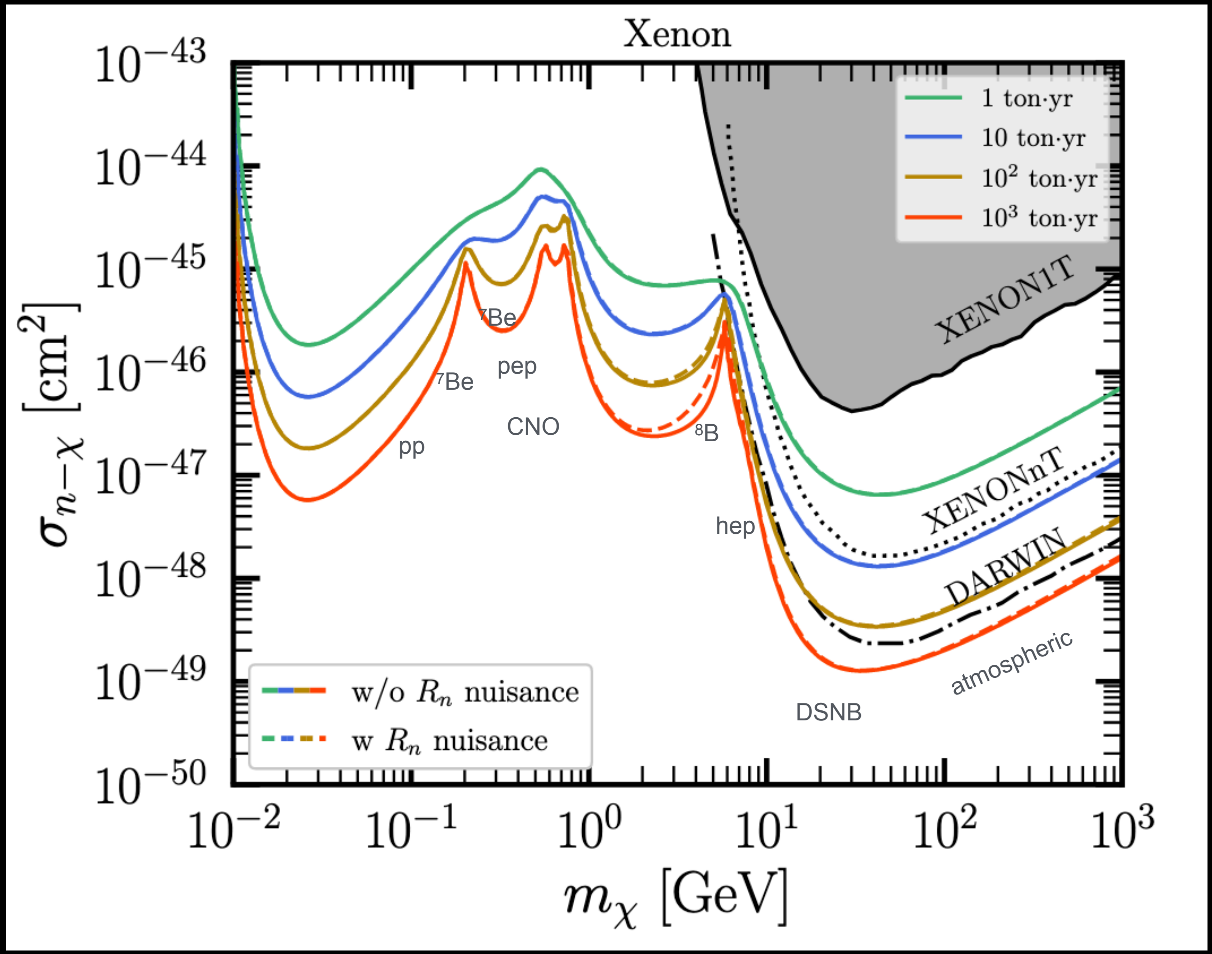
$$F(q^2) = 3\frac{j_1(qR_0)}{qR_0}\, e^{-\frac{1}{2}(qs)^2}$$

- Rp=4.78fm (fixed)
- vary around Rn = 4.78 fm (central value)
- assume 10% uncertainty on Rn

Helm parametrization

$$R_0 = \sqrt{\frac{5}{3}\left(R_X^2 - 3s^2\right)} \qquad (X = p, n)$$

- Low WIMP masses and incoming neutrino energies: the zero momentum transfer limit is a good approximation.
- With increasing neutron mean-square radius, nuclear size increases. The loss of coherence happens for smaller q. As Rn increases, both the neutrino background and the WIMP event rate are (slightly) suppressed.



Aristizabal, VDR, Flores, Papoulias JCAP 01 (2022) 01, 055

(2.c): Neutrino magnetic moments/transitions

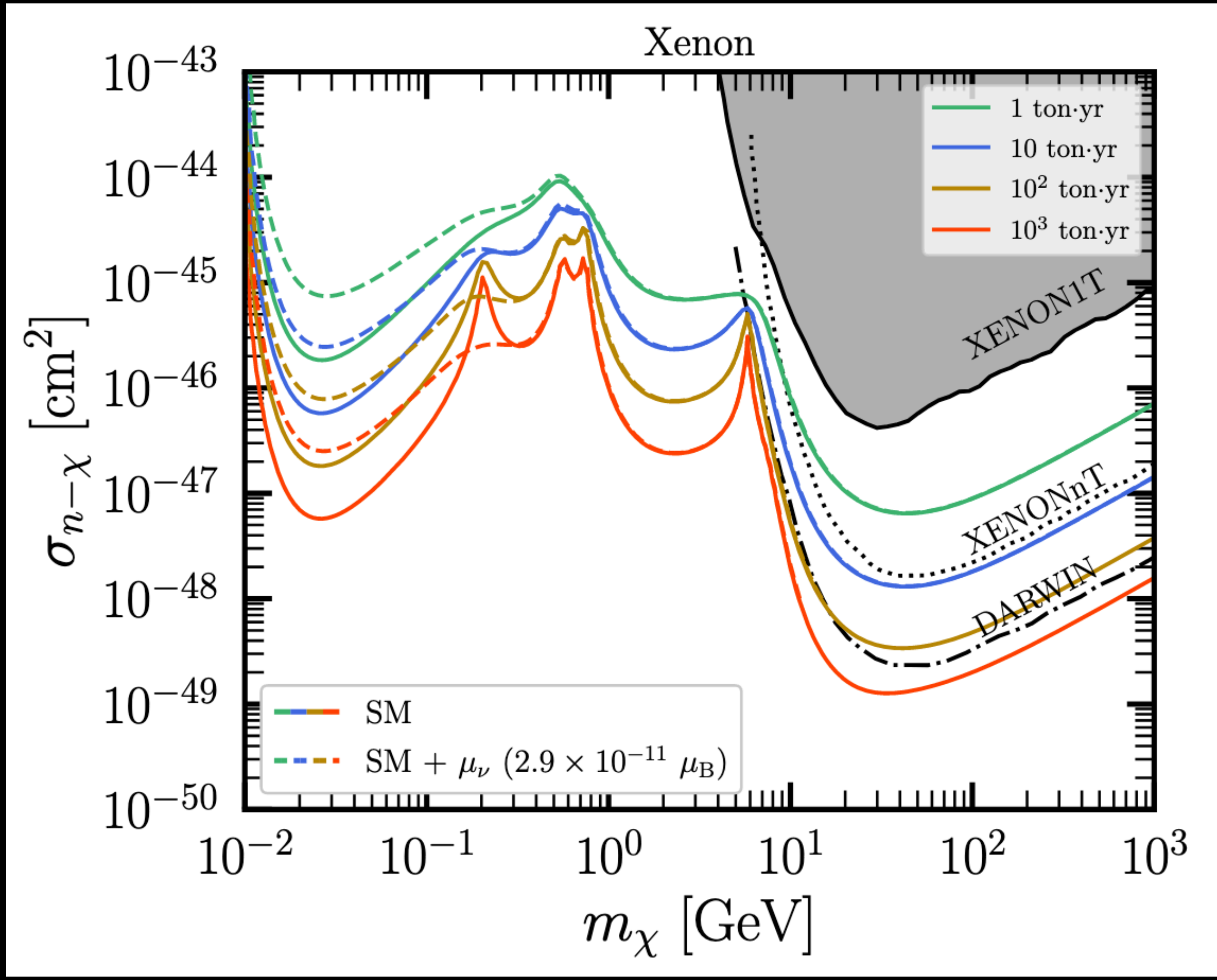
In the presence of a neutrino magnetic moment, the CEνNS cross section is increased by:

$$\frac{d\sigma_\gamma}{dE_r} = \pi\alpha_{\rm em}^2\, Z^2 \frac{\mu_{\rm eff}^2}{m_e^2}\left(\frac{1}{E_r} - \frac{1}{E_\nu}\right) F^2(q^2)$$

Vogel, Engel et al. PRD39(1989)

$\mu^2_{\rm eff}$ is an effective parameter (in Bohr magneton units μ_B) that encodes the neutrino magnetic and electric dipole moments (and transitions).

- The main feature of the new coupling is spectral distortion.
- We fix $\mu^2_{\rm eff} = 2.9\times10^{-11}\mu_B$, which corresponds to the 90% CL limit reported by GEMMA and XENON1T.
- Up to WIMP masses ~ 0.2 GeV the discovery limit worsens, because of the background enhancement.
- In the region of large transfer momentum, the Coulomb divergence fades away.



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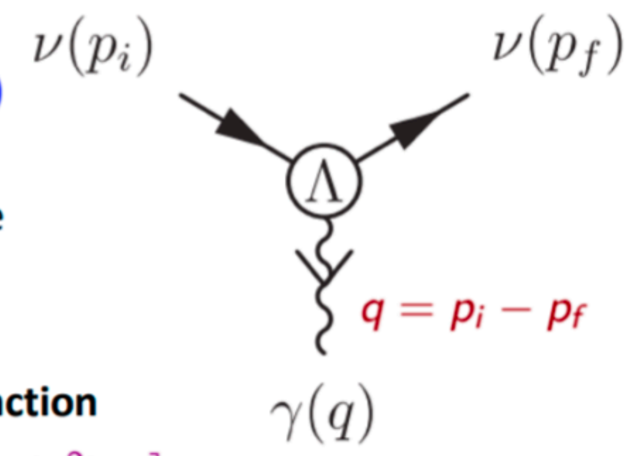
Electromagnetic interactions

For neutrinos the electric charge is zero and there are no electromagnetic interactions at tree level. However, such interactions can arise at the quantum level from loop diagrams at higher order of the perturbative expansion of the interaction.

- **Effective Hamiltonian** $\mathcal{H}^{(\nu)}_{\text{em}}(x) = j^{(\nu)}_{\mu}(x)A^{\mu}(x) = \sum_{k,j=1} \overline{\nu_k}(x)\Lambda^{kj}_{\mu}\nu_j(x)A^{\mu}(x)$

- We are interested in the neutrino part of the amplitude which is given by the following matrix element $\langle\nu_f(p_f)|j^{(\nu)}_{\mu}(0)|\nu_i(p_i)\rangle = \overline{u_f}(p_f)\Lambda^{fi}_{\mu}(q)u_i(p_i)$



- The electromagnetic properties of neutrinos are embedded by the **vertex function**

$$\Lambda_{\mu}(q) = (\gamma_{\mu} - q_{\mu}\not{q}/q^2)\left[F_Q(q^2) + F_A(q^2)q^2\gamma_5\right] - i\sigma_{\mu\nu}q^{\nu}\left[F_M(q^2) + iF_E(q^2)\gamma_5\right]$$

Lorentz-invariant form factors: charge, anapole, magnetic, electric

$q^2 = 0 \implies$ $\mathfrak{q}$, a, μ, ε

Charge and anapole moment — Magnetic and electric dipole moments

[C. Giunti, A. Studenikin, Neutrino electromagnetic interactions: A window to new physics, Rev Mod Phys, 87, 531 (2015), Arxiv:1403.6344*]*

taken from M. Cadeddu, Magnificent CEvNS 2020